# An investigation into the edge gluing of green *Eucalyptus grandis* lumber using an one-component polyurethane adhesive

by
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## Abstract

South Africa is a timber-scarce country with a relatively small portion of only about 1% of its total land area being used for commercial forestry. Due to an increasing demand for timber but restrictions regarding the expansion of plantation area, the country is expected to experience a shortage of softwood supply for saw logs in the near future. The predominant hardwood species *Eucalyptus grandis* is, despite good strength and stiffness properties, at present for the most part used for wood chip or pulp and paper production. This is mainly owing to growth stresses, splitting, and the low dimensional stability of the wood, which therefore could not comply with the requirements of the South African national standard for sawn eucalyptus timber (SANS 1707-1 2010). As wood defects often develop or aggravate during the drying stage, the edge-bonding of *Eucalyptus grandis* lumber in its wet state was considered to possibly inhibit this behaviour. This study consisted of two experiments. In the first experiment shear tests were used to determine the influence of various material and processing variables on the bonding quality of green *Eucalyptus grandis* wood with a moisture-curing one-component polyurethane adhesive. The experimental design for this investigation comprised 16 groups with different combinations of parameters for wood density, moisture content, adhesive spread rate and pressure. Ten samples per group were tested for shear strength. The penetration behaviour of the one-component polyurethane adhesive into the wood structure was additionally investigated on samples with extreme results, employing a micro CT scanner. All tested samples clearly exceeded the minimum shear strength for cross-laminated timber products according to EN 16351 (2015). Better results were generally obtained for samples with an increased moisture content of roughly 60% compared to specimens with a lower moisture content around fibre saturation point, which could be linked to an enhanced adhesive penetration. In the second experiment the potential of edge gluing green *Eucalyptus grandis* boards before kiln drying in order to inhibit the development of certain wood defects was investigated. Edge-glued panels were produced from wet material above fibre saturation point and kiln-dried together with non-edge-bonded control boards from the same material source. After drying, the panels were sawn apart into single boards, graded regarding the development of check, split, bow, cup and twist and compared to the results obtained for the control boards. The ability of stress-relief grooves in boards to reduce the development of defects was also investigated. The results showed that the edge gluing of green *Eucalyptus grandis* lumber before kiln drying could not decrease the number of board rejections according to the SANS 1707-1 (2010) requirements for sawn eucalyptus timber. Cup could be significantly decreased, while twist was only reduced for boards without pith. Stress-relief grooves did not have a significant influence on the development of any of the investigated defects but caused severe deformation and damage in some of the boards. Further investigations should be carried out on mass timber products such as cross-laminated timber, where green edge-glued and kiln-dried *Eucalyptus grandis* panels could be used as a component.


**Keywords:** *Eucalyptus grandis*, 1C PUR, edge bonding, green gluing of timber, micro CT scanner, wood defects, warp, stress-relief grooves

## Opsomming

Suid Afrika het min boshulpbronne met slegs 'n klein gedeelte, van ongeveer 1%, van sy landoppervlak wat gebruik word vir bosbou. Daar word verwag dat 'n groeiende vraag na soliede saaghout en krimpende plantasie-area sal lei tot 'n tekort in naaldhoutprodukte in die nabye toekoms. Die mees aangeplante loofhoutspesie, *Eucalyptus grandis*, word ten spyte van goeie sterkte -en styfheidseienskappe hoofsaaklik vir pulp en spaanderproduksie gebruik. Dit is hoofsaaklik as gevolg van groeispannings, spleting, en swak dimensionele stabiliteit van die hout – wat veroorsaak dat dit nie voldoen aan die vereistes van soliede *Eucalyptus* saaghout nie (SANS 1707-1 2010). Houtdefekte ontwikkel of vererger dikswels gedurende die drogingsfase en hierdie studie ondersoek die inhiberende potensiaal op defekformasie van die aanmekaarlym van planke terwyl dit steeds nat is. Die studie bestaan uit twee eksperimente. In die eerste eksperiment is skuiftoetse gebruik om die invloed van verskeie material –en prosesseringsveranderlikes op die lymlaskwaliteit van groen (nat) *Eucalyptus grandis* planke wat met 'n enkelkomponent poli-uretaanlym gelym is. Die eksperimentele ontwerp vir hierdie studie bestaan uit 16 groepe wat met verskillende kombinasies van houtdigtheid, voggehalte, lymhoeveelheid, en druk geheg is. Tien monsters per groep is getoets vir skuifsterkte. Die penetrasiegedrag van die lym in die houtstruktuur is ondersoek met mikro-CT skandering. Al die getoetsde monsters het die minimum skuifsterktevereiste volgens die EN16351 (2015) standaard behaal. Beter resultate is oor die algemeen verkry met hoër voggehalte van bykans 60% in vergelyking met monsters wat by veselsversadigingspunt was – waarskynlik as gevolg van beter lympenetrasie. In die tweede eksperiment is die potensiaal ondersoek van nat aanmekaarlym van planke in panele voor oonddroging om drogingsdefekte te minimeer . Kant-gelymde panele is vervaardig van groen (nat) *Eucalyptus grandis* en gedroog saam met individuele kontroleplanke . Na droging is die panele weer losgesny in planke en gegradeer ten opsigte van oppervlakkrake, spleting, boogtrek, koppievorming, en draaitrek en vergelyk met die individuele kontroleplanke. Die vermoë van spanningsgleuwe in die planke om defektvorming te inhibeer is ook ondersoek. Die resultate wys dat die kantlym van groen *Eucaluptus grandis* planke voor oonddroging nie die plank afgradering volgens SANS 1707-1 (2010) kon verminder nie. Koppievorming kon beduidend verminder word, terwyl draaitrek slegs verminder kon word in nie-pitplanke. Spanningsgleuwe het nie 'n beduidende invloed gehad op die vorming van enige van die defekte nie, maar het erge deformasie en skade in sommige planke veroorsaak. Verdere ondersoeke moet gedoen word op groot-houtprodukte ("mass timber products") soos kruis-gelamineerde hout, waar heel panele gebruik kan word as 'n komponent.

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# Chapter 1.
# Introduction

## 1. Background

In South Africa only about 1% of the total land area is used for commercial forestry. These approximately 1.27 million ha of forest plantations are mostly composed of *Pinus* (51%) and *Eucalyptus* (40%) species (DAFF 2012, DAFF 2015). Over the past twenty years afforestation in the country has declined. This was mainly due to a scarcity of suitable land and restrictions on expanding plantation areas as new regulations regarding water usage were introduced by the government. Other factors included the privatisation of forests formerly belonging to the state, with private forest owners often preferring a more regular cash flow over long-term returns and therefore a short-rotation production of pulpwood over sawlogs. At the same time the area used for short-rotation production, i.e. pulpwood purposes, increased markedly (Chamberlain et al. 2005, DAFF 2015). Since the demand for saw logs is steadily growing but afforestation is stagnating, a severe shortage of timber is expected within the next two decades (Crickmay et al. 2005). Consequently, this will lead to further increasing sawn timber prices within the country and thus decreased competitiveness on the international market. South Africa may therefore become a net importer of timber, which would have a negative impact on many forestry subsectors, such as the sawn lumber industry. Although the forestry sector produces only about 1% of South Africa's gross domestic product (GDP), it is considered very important for the socio-economic stability of the country, since it provides about 170 000 direct employment opportunities and about 850 000 people are dependent on this sector for a living, mainly in rural areas with little economic alternatives (Chamberlain et al. 2005, DAFF 2015).

A possible solution to meet the growing needs for timber could be the utilisation of hardwood species of which the vast majority is currently used for pulp and paper products and wood chips (83.6% in 2013, DAFF 2015). This would not only add more value to the product but also create additional employment possibilities within the country due to an increased labour intensity compared to the pulp sector (DAFF 2012). With approximately 270 000 ha of plantation area, the fast-growing *Eucalyptus grandis* is the predominant hardwood species in South Africa (DWAF 2009). Several million tons of *Eucalyptus grandis* chips are exported annually (Chamberlain et al. 2005), which could potentially rather be used for higher value products, such as sawn timber. The reason *Eucalyptus* timber is currently rarely processed into structural lumber in South Africa is mainly due to processing problems associated with poor dimensional stability, splitting, and checking after drying. Unseasoned and finger-jointed *Eucalyptus grandis* lumber of different age-classes between 5 and 18 years was investigated by Crafford (2013). Although good results were obtained for strength and stiffness, the requirements for sawn wood according to the SANS 1783-2 (2005) could not be met as the test boards exceeded the maximum values for twist and checking.

A new processing method for *Eucalyptus* has recently been conceptualised at Stellenbosch University in order to ameliorate some of the processing problems that have prevented this genus from being used on a large scale for solid wood products. Since most wood defects either originate or aggravate during the drying stage, the edge gluing of several sawn, wet *Eucalyptus grandis* boards before kiln drying was considered to potentially have a positive effect on the reduction of deformation and the development of so-called "drying defects". Furthermore, the edge-glued panels could be used for a variety of end products. It could be ripped up into sawn lumber again, used as panel products, or it could be used as a component for mass timber such as cross-laminated timber (CLT).

The gluing of wet, unseasoned lumber above fibre saturation point (FSP) is often referred to as “green gluing” and has been investigated over the past decade with a variety of wood species and adhesive systems. Besides economic advantages due to an altered production flow, certain products, e.g. finger-jointed lumber, turned out to be superior in quality to the dry-wood bonded equivalents (Sterley 2004, Källander et al. 2008). At the time of this study no research on green edge-glued *Eucalyptus grandis* lumber was available to the author’s knowledge. It was therefore necessary to gain knowledge of the adhesion behaviour between *Eucalyptus grandis* wood and one-component polyurethane (1C PUR) adhesives as well as to determine how different material and processing variables can influence the bonding quality. The effect of edge gluing wet *Eucalyptus grandis* boards on the development of warp and other drying-related defects also had to be quantified in order to determine the feasibility of the process.

## 2. Objectives

The objectives of this study were:

1. To determine how different material and processing variables (wood density, moisture content, pressure and adhesive spread rate) influence the bonding quality of unseasoned, edge-wise glued *Eucalyptus grandis* wood, when using a 1C PUR adhesive.

2. To investigate how the age of the timber, the presence of pith, finger jointing, stress-relief grooves and the edge gluing of green *Eucalyptus grandis* boards influence the development of certain wood defects, namely check, split and warp in the form of bow, cup and twist.

## 3. Structure of thesis

This thesis consists of four chapters. Chapter 1 contains the introduction to this thesis. It is followed by Chapter 2 and 3, which comprise two separate experiments. Chapter 4 summarises all obtained research results of this study.

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# Chapter 2.
# Influence of processing parameters and wood properties on the edge gluing of green *Eucalyptus grandis* with an one-component PUR adhesive

## 1. Introduction

In South Africa only about 1% of the total land area is used for commercial forestry. These approximately 1.27 million ha of forest plantations are mostly composed of *Pinus* (51%) and *Eucalyptus* (40%) species (DAFF 2012, DAFF 2015). Over the past twenty years afforestation in the country has declined. This was mainly due to a scarcity of suitable land and restrictions on expanding plantation areas as new regulations regarding water usage were introduced by the government. At the same time the amount of hectares used for short-rotation production, i.e. pulpwood purposes, increased markedly (Chamberlain et al. 2005, DAFF 2015). Since the demand for roundwood is steadily growing but afforestation is stagnating, a shortage of softwood sawn timber is expected within the next two decades. As a consequence South Africa may become a net importer of softwood lumber (Crickmay et al. 2005). That in turn would have a negative impact on many forestry subsectors, which are considered very important for the socio-economic stability of the country (DAFF 2015).

A possible solution to meet the growing needs for timber could be the utilisation of hardwood species of which the vast majority is currently used for pulp and paper products and wood chips. This would not only add more value to the product but also create additional employment possibilities within the country due to an increased labour intensity compared to the pulp sector (DAFF 2012). With approximately 270 000 ha of plantation area, the fast-growing *Eucalyptus grandis* is the predominant hardwood species in South Africa (DWAF 2009). Unseasoned and finger-jointed *Eucalyptus grandis* sawn timber of different age-classes between 5 and 18 years was investigated by Crafford (2013) regarding its suitability for structural applications. Although good results were obtained for strength and stiffness, the requirements for sawn wood according to the SANS 1783-2 (2005) could not be met as the test boards exceeded the maximum values for twist and checking. Since most wood defects either originate or aggravate during the drying stage, the edge gluing of several sawn *Eucalyptus grandis* boards before kiln drying was considered to possibly reduce the development of the so-called "drying defects".

The gluing of wet, unseasoned lumber above fibre saturation point is often referred to as "green gluing" and has been investigated over the past decade with a variety of wood species (mostly softwoods) and adhesive systems. Besides economic advantages due to an altered production flow (Sterley 2004) and the potential of adding value to lower grade timber by lamination (Serrano et al. 2010), certain products, like finger-jointed lumber, turned out to be superior in quality to the dry-wood bonded equivalents (Pommer and Elbez 2006). At the time of this study no research on green edge-glued *Eucalyptus grandis* lumber was available to the author's knowledge. The only hardwoods for which research results on green-glued adhesive joints were available were beech (*Fagus sylvatica*) (Properzi et al. 2003) and finger-jointed oak (*Quercus conferta* L.) (Karastergiou et al. 2008), showing an increased bonding strength of polyurethane (PUR) adhesives compared to phenol-resorcinol-formaldehyde (PRF) and melamine-urea-formaldehyde (MUF) adhesives and proving the feasibility of green gluing with PUR adhesives and high-density species, respectively. In order to investigate the feasibility of edge gluing wet *Eucalyptus grandis* boards it was therefore important to carry out a preliminary study to gain knowledge of the adhesion behaviour between *Eucalyptus grandis* wood and one-component polyurethane (1C PUR) adhesives as well as to determine how different material and processing variables can influence the bonding quality.

The objective of this study was to determine the influence of material variables (basic density and moisture content) and processing variables (adhesive spread rate and pressure) on the bonding strength of unseasoned, edge-wise glued *Eucalyptus grandis* wood, using a moisture-curing 1C PUR adhesive.

## 2. Literature review

### 2.1 Eucalyptus grandis

*Eucalyptus grandis* is a tall, fast-growing hardwood species from the *Myrtaceae* family. Originally from Australia, the species was introduced in South Africa around 1885 and at present, with approximately 270 000 ha of plantations, is the predominant hardwood species in the country (DWAF 2009, Orwa et al. 2009). An exceptionally high growth rate of 20 to 30 $m^3$/ha/year, together with other favourable properties such as the excellent form of trunk, ease of care and high strength values make *Eucalyptus grandis* the most commercially planted eucalypt worldwide among more than 600 different *Eucalyptus* species (Sánchez Acosta et al. 2008, McMahon et al. 2010).

*Eucalyptus grandis* trees can be found up to an altitude of 2 700 m and are able to grow within a temperature range from -1 to 40 ˚C and 100 up to 1 800 mm mean annual rainfall (Orwa et al. 2009). In South Africa, industrially used *Eucalyptus grandis* trees are almost exclusively cultivated on commercial plantations, of which about 82% are certified by the Forest Stewardship Council (FSC) (DAFF 2012). It is a so-called “diffuse-porous” hardwood species, which means that only little difference can be observed between earlywood and latewood, since distribution as well as size of the different cell types (i.e. tracheids, fibres, vessels and parenchyma) are fairly uniform across the growth ring (Dinwoodie 2000).

Although *Eucalyptus grandis* was initially introduced for board and paper production, various products like flooring, furniture and other internal applications were produced from the wood since then (McMahon et al. 2010). However, the utilisation of *Eucalyptus grandis* sawn timber for structural purposes is relatively rare. This is mainly due to its tendency to check and split as well as the low dimensional stability of the wood, which causes the boards to warp extensively and hence could not comply with the South African national standard for sawn eucalyptus timber SANS 1707-1 (2010) (Crafford 2013).

### 2.2 Adhesion theory

At present the majority of wood products are bonded with adhesives. This offers new opportunities of utilisation as wood properties can be homogenised, products with desired dimensions can be flexibly designed, and low-quality wood can be upgraded to structural timber. The most popular products are building materials and engineered wood products such as oriented strand board (OSB), particleboard, fibreboard and plywood (Sterley 2004, Gardner et al. 2014).

When the gluing of timber is investigated, it is crucial to understand the interaction between adhesive and wood material as well as how the quality of a bond can be affected by certain factors.

Wood is a porous material and thus allows liquid resin to penetrate into its cellular structure. *Eucalyptus grandis* as a hardwood consists of parenchyma, fibres, tracheids and vessels and compared to plantation pine species in South Africa is generally higher in density (Crafford 2013), which is mainly attributed to the thicker cell walls and smaller lumina (Dinwoodie 2000). The lower porosity of hardwoods makes it more difficult for the adhesive to move into the wood, with the permeability varying among different species due mostly to the variation in vessel diameter (Frihart and Hunt 2010).

The physical interaction between the viscous adhesive and the cell structure of the wood is defined as mechanical interlocking (see figure 1, link 4 and 5). The resin penetrates the porous wood tissue, fills up the lumen and sets hard, therefore providing stiffness and bonding strength (Gardner et al. 2014). Kamke and Lee (2007) revealed that mechanical interlocking takes place both above and below the wood surface. This theory is corroborated by the chain-link model designed by Marra (1992) (figure 1).

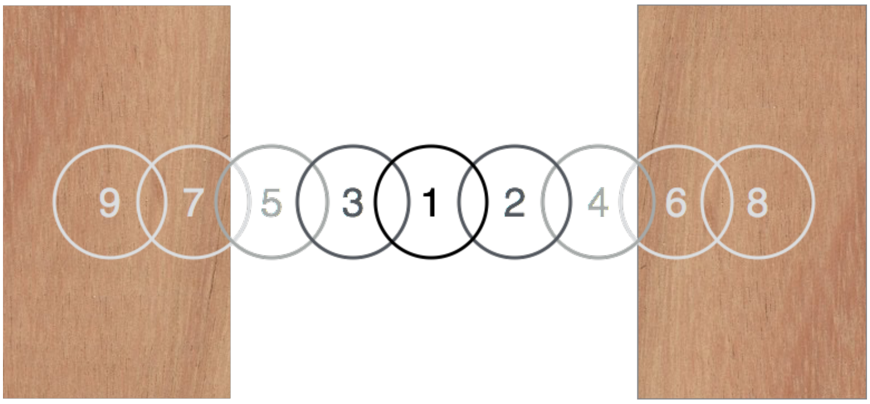


*Figure 1: Adhesive chain-link analogy model for an entire bondline. Adapted from Marra (1992).*

Figure 1 shows a chain-link model between two bonded substrates. Marra (1992) defined a glueline as the area between link 1 and 5, whereas the term "bondline" describes the entire link-chain from 1 to 9, including the subsurface zones where the wood tissue is penetrated by the adhesive.

According to Gardner et al. (2014), the model in figure 1 can be explained as follows:

Link 1: The area in the very middle of the glueline: Composed of pure adhesive.
Links 2 and 3: The adhesive boundary layers: Already influenced by the substrate during curing.
Links 4 and 5: The adhesion layer: Mechanical interlocking or chemical bonding takes place.
Links 6 to 9: The wood cells: Penetrated by the adhesive.

The penetration of the adhesive into the wood cell structure can be divided into two groups:

1) "Gross penetration", which describes the hydrodynamic flow of the adhesive when forced into cell lumina by external compression such as clamping.

The flow usually follows the path of least resistance. For hardwoods, like *Eucalyptus grandis*, this is through vessels elements, which run along the longitudinal direction and are often interconnected through porous end wall plates. Significantly lower is the permeability in both the radial and the tangential direction. Radial flow occurs by the way of rays, whereas the fluid conduction in the tangential direction depends on the existence of pits to connect the different cell types present in hardwoods. The permeability is generally increasing from the centre to the outer sapwood of a tree, as the heartwood cells become mostly blocked by gum or resin depositions. Moreover, "diffuse-porous" hardwoods, such as *Eucalyptus grandis*, show a markedly decreased permeability compared to "ring-porous" species, owed to their smaller earlywood vessels (Kamke and Lee 2007).

2) "Cell wall penetration" on the other hand is defined as the flow or diffusion of the resin into the cell walls and micro fissures, forced by oppositely charged molecular components of the adhesive and the wood, both aspiring neutral state (Kamke and Lee 2007).

However, according to Lehringer and Gabriel (2014) neither the chemical nor the physical interaction between 1C PUR adhesives and wood cell walls are completely understood yet. Studies have shown that due to a high molecular weight 1C PUR adhesives are not capable of penetrating into cell walls. Since it is yet unclear if 1C PUR adhesives can flow through the pits of *Eucalyptus grandis* cell walls, the only way for the glue to move deeper into the wood structure might be by the way of vessel elements. Although no clear correlation between penetration depth and bonding quality could be determined to date, it is assumed that deeper adhesive penetration can enhance the ability of the bondline to distribute and transfer stresses that occur under load, due to a more gradually change in stiffness (Sterley 2012). It may as well contribute to improve the bonding strength, as the increased surface contact allows enhanced chemical interaction between wood and adhesive, also known as “wetting” (Kamke and Lee 2007). Wetting describes the formation of secondary-force (i.e. intermolecular) bonding, such as van der Waals forces, dipole-dipole forces or hydrogen bonds, which are considered to be the most significant mechanism in wood bonding (Simpson 1999).

## 2.3 One-component polyurethane adhesives

According to Lehringer and Gabriel (2014), the first one-component polyurethane (1C PUR) adhesive system was invented by Otto Bayer in Germany, almost 80 years ago. Although in the beginning it was primarily used by the textile industry as well as for non-structural wood applications, the adhesive was finally applied for engineered wood products for the first time in 1985. Over the last two decades 1C PUR adhesives gained in importance for the industrial manufacturing of engineered wood products, especially for load bearing lumber, such as glulam, finger-jointed lumber or cross-laminated timber (CLT). Nowadays polyurethane adhesives are widely accepted by the wood processing industry as a secure, reliable and versatile alternative to conventional systems such as melamine-urea-formaldehyde (MUF) and phenol-resorcinol-formaldehyde (PRF). This is not least due to the introduction of European standards concerning specific requirements and test standards for adhesive systems other than phenolic and aminoplastic (EN 15416-2 to 5 2006, EN 15425 2008). A few favourable properties include a reduced press time, 100% solid content, invisible bondlines and a long shelf life. In addition, no formaldehyde is used, the adhesives are cold-setting and significantly lower spread rates are needed compared to MUF or PRF adhesives in order to achieve ”stable and reliable” bondlines. 1C PUR bondlines also show an increased ductility, a characteristic that differs significantly from aqueous or formaldehyde-based adhesives, which are usually more brittle with a higher modulus due to a high crosslink density. A more elastic bondline can reach a higher fracture strength and therefore reduce peak stresses at the wood-adhesive interface as the occurring stresses are more equally absorbed in both wood and bondline. This might be crucial in the context of green gluing as strong tensile stresses are created during kiln drying, owed to the shrinkage of the wood (Källander et al. 2008). The increased ductility of the bondline may lead to a decreased percentage of wood failure but to an increase in bonding strength. Hence wood failure percentage (WFP) as a criteria for bonding quality of 1C PUR adhesive bonds should be considered questionable (Xiao et al. 2007, Lehringer and Gabriel 2014).

As a so-called “moisture-curing” system, moisture is used as the second component to react and thus curing is initiated by the reaction of isocyanate and water, which is taken from both the wood and the surrounding air. This reaction creates amines and carbon dioxide, with the latter one foaming the glueline and hence entailing the risk of cavities in the bond but also providing the glue with its “gap-filling” properties (Sterley 2004).

$$R - NCO + H_2O \rightarrow R - NH_2 + CO_2$$

(Zeppenfeld and Grunwald 2005)

Weaver and Owen (1995) found out that isocyanate reacts preferably, and thus quicker, with water than with all other wood compounds that contain hydroxyl groups. This concludes that the adhesion between 1C PUR adhesives and the wood surface "is owed to physical anchorage effects and possibly the formation of van der Waals interactions and hydrogen bonds" (Lehringer and Gabriel 2014, p.410).

As "green gluing" became more interesting to the wood industry over the last 20 years, several cold-setting adhesive systems were developed and examined, mostly for finger jointing purposes. Besides more conventional systems, such as Greenweld, SoyBond or epoxy adhesives, 1C PUR adhesives were evaluated as suitable for green gluing (Källander et al. 2008). The fact that the hardening chemistry of moisture-curing 1C PUR adhesives is well-suited for bonding wet wood provides additional advantages. Studies done by Sterley (2004 and 2012) exhibited deeper penetration into green wood than dry wood, performing superior compared to PRF systems, while the rapid increase in molecular size during the curing process prevents a "starved" glueline, as it would happen with conventional adhesives due to excessive absorption. Moreover, no mixing at the processing stage is necessary since mainly the moisture of the wet wood is used as the second component to react with.

On the other hand, 1C PUR adhesives have shown poor adhesion quality and high delamination values in combination with dry, high-density wood. Since it is difficult for the resin to penetrate a dense wood tissue at a low moisture content, too much adhesive gets squeezed out of the joint when pressure is applied on the bond. Consequently, the resulting glueline is too thin and therefore not able to absorb occurring stresses properly (Xiao et al. 2007, Källander et al. 2008). Additionally, there is uncertainty regarding the long-term behaviour, such as creep, of 1C PUR adhesive bonds of green-glued products. However, according to Källander et al. (2008) and Lehringer and Gabriel (2014) this is primarily due to a lack of studies as well as inappropriate measurement methodology, which is leading to contradicting results.

### 2.4 Important variables for "green gluing"

Wood is a hygroscopic material, which means it is able to absorb and desorb water in exchange with the surrounding air in order to reach the so-called "equilibrium moisture content" (EMC) – the state when wood is neither losing nor gaining moisture. The actual moisture content (MC) of a piece of wood therefore depends on temperature and relative humidity of its surrounding environment (Wagenführ and Scholz 2012). In the wood sector the term "green" refers to freshly sawn, undried timber above fibre saturation point (FSP), i.e. a minimum wood MC of roughly 30%. Below FSP, water is bound in the cell walls (i.e. "bound water") by intermolecular attraction and is transported through the tree by diffusion. Above FSP so-called "free water", which is transported by capillary forces and resides in the cell lumina, adds to the already fully saturated cell wall microsystem (Glass and Zelinka 2010). In this context it should also be mentioned that the theory of an exact FSP in reality only rarely exists and rather has to be considered as a certain range of moisture contents. This is because the wood surface dries quicker than the core and thus some free water might still remain in the cavities of the interior while at the same time cell walls close to the surface are not completely saturated with water anymore (Dinwoodie 2000).

Gluing green wood differs from dry-wood bonding in several aspects as the elevated amount of water in the wood has an impact on certain wood properties as well as its interaction with adhesives. This applies particularly for moisture-curing adhesive systems, such as 1C PUR, which employ water as second component to react and thus differ considerably from aqueous or formaldehyde-based adhesives.

The following section summarizes material and processing variables which have to be considered for the investigation of edge gluing of green *Eucalyptus grandis* wood with a moisture-curing 1C PUR adhesive in regard to adhesion quality and bonding strength.

1) Wood density

Hardwoods consist of four different cell types, namely parenchyma, tracheids, fibres and vessels. The density of the wood is therefore defined by the ratio between cell wall and cell lumen as well as the amount and size of vessel elements present in the wood (Wagenführ and Scholz 2012). An increased wood density, as it is common for hardwood species, is generally correlated with enhanced mechanical properties, viz. strength and stiffness of the material. In terms of bonding quality it can however lead to increasing delamination, as fewer cavities provide less space for the adhesive to penetrate. This in turn can lead to a squeeze-out of the adhesive at the pressing stage, leaving a glueline too thin to properly absorb occurring stresses (Källander et al. 2008, Frihart and Hunt 2010, Sterley 2012).

2) Moisture content

Since moisture-curing 1C PUR adhesives primarily employ wood-contained water as the second component to react with, an increased MC consequently entails a faster curing reaction. Generally, an elevated MC above FSP seems favourable for this type of adhesive due to its above described reaction chemistry (see section 2.3). This theory is supported by the findings of Xiao et al. (2007), where poor adhesion quality was obtained for dry high-density wood.

3) Adhesive spread rate

According to Sterley (2012), 1C PUR adhesives are able to penetrate the cell structure of wet softwoods up to twice as deep as compared to dry material. Due to the higher absorption, an increased adhesive spread rate should be employed as recommended for dry-wood applications by the manufacturer in order to avoid “starved” gluelines. However, it is neither known if 1C PUR adhesives can penetrate through *Eucalyptus grandis* cell walls, nor if a deeper penetration of glue into vessels can contribute significantly to the actual bonding strength (Kamke and Lee 2007).

4) Pressure

Since wet lumber is generally softer and thus more flexible than dry lumber, less pressure is needed to achieve good contact between two wood surfaces. Pressure should also be reduced in order to avoid damage of the wood structure, which has decreased strength and stiffness properties at its green state. Furthermore, as *Eucalyptus grandis* is of higher density, the glue can get pressed out of the joint instead of into the wood structure when high pressure is applied, leading to a too thin bondline. On the other hand a lack of pressure can also impair the quality of the bondline due to insufficient penetration resulting in a thick glueline with $CO_2$ induced cavities (Sterley 2012).

5) Press time

The elevated MC in green wood considerably accelerates the hardening reaction of moisture-curing 1C PUR adhesives. Thus, under warm and humid conditions, press time can be reduced by up to 30% from the manufacturer's recommendations for dry wood (pers. comm. Ferreira-Netto, Henkel SA, May 2016). However, if pressure is applied for too little time, it might not be possible to force the adhesive deep enough into the cell structure. This would result in reduced mechanical interlocking and consequently in decreased bonding strength. Furthermore, Sterley (2012) proposed that a prolonged press time may have a positive impact on delamination properties and shear strength of bonded hardwoods.

6) Assembly time

Due to the quicker curing of 1C PUR adhesives when applied on wet wood, the assembly time stated by the manufacturer is as well reduced by up to 30% (pers. comm. Ferreira-Netto, Henkel SA, May 2016). Since resin is only able to flow through the porous wood structure at its fluid state, sufficient time to assemble the material is crucial in order to apply pressure before the adhesive starts to cure. This allows the glue to wet the wood and thus to avoid thick and weak bondlines (Simpson 1999). As the assembly time might have to be adjusted to certain material or environment conditions (i.e. wood MC or temperature and humidity), this can be done by choosing a suitably formulated adhesive model. The Loctite / Purbond models are ranging from two to 70 minutes assembly time at standard conditions, i.e. 20°C temperature, 65% relative air humidity and 12% wood MC (see figure 2).

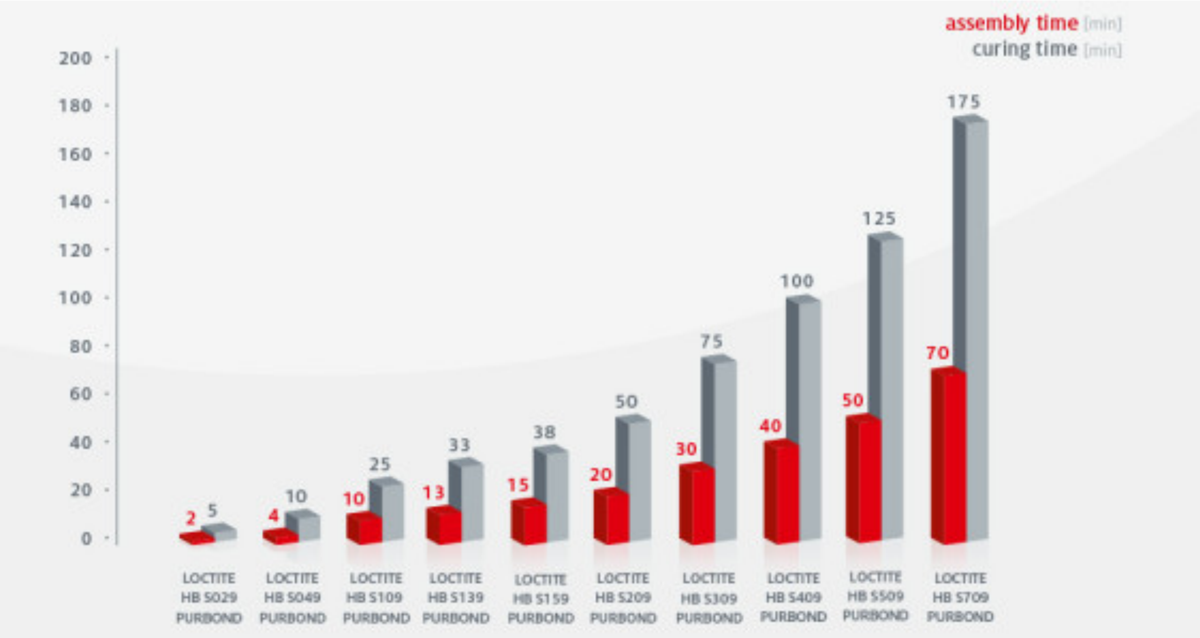


*Figure 2: Loctite / Purbond 1C PUR adhesive products with varying assembly and curing times (Henkel 2016).*

7) Pressing temperature

Heat treatment (i.e. elevated temperature compared to standard conditions) during the gluing stage is considered to enhance particular properties of certain types of adhesive. By lowering the viscosity of the glue while simultaneously expanding the wood structure it can contribute to improved penetration (Kamke and Lee 2007). However, investigations by Xiao et al. (2007) lead to the conclusion that in the case of 1C PUR adhesives an increased pressing temperature does not result in an increased penetration depth.

8) Humidity and ambient temperature

Both variables have a significant impact on the behaviour of the adhesive. A higher humidity causes a faster reaction of moisture-curing 1C PUR adhesives due to an increased availability of water in the surrounding air. The temperature influences the viscosity of the resin and, if below the demanded minimum value, can impede penetration and prolong the curing process by up to 50% due to the reduced mobility of the adhesive (pers. comm. Ferreira-Netto, Henkel SA, May 2016). However, both humidity and temperature are mostly subject to changing climate conditions and thus can often not be perfectly controlled or kept at a steady level within an industrial environment.

9) Wood surface quality

Another important factor is the quality of the wood surface. According to Gardner et al. (2014) so-called "weak-boundary-layers" (WBL) can occur in the interface between the adhesive and the wood material, reducing the quality of the bond until culminating in the eventual failure of the glueline. WBL can be caused by any kind of mechanical damage during the wood processing stage as well as by chemical reasons, such as contaminating extractives. Those extractives are migrating to the surface during the drying stage, but can be easily removed by planing, which should thus be carried out shortly before gluing. This is also because the wood surface loses moisture quickly after being processed and is therefore more prone to shrink and warp and thus become uneven, which in turn causes cavities and stress concentrations in the glueline (Simpson 1999). Experience has shown that with increasing MC it gets more difficult to obtain a clean and smooth surface of *Eucalyptus grandis* wood (pers. comm. Ferreira-Netto, Henkel SA, May 2015). However, according to Gardner et al. (2014) it is not yet completely known whether different levels of roughness of the wood surface have a positive or negative impact on the bonding quality.

### 2.4.1 Limitation of variables

1) Adhesive formulation

Since Henkel is the only distributor of commercial moisture-curing 1C PUR wood adhesives in South Africa, the scope of this study was limited on the investigation of the interaction between *Eucalyptus grandis* wood and a certain 1C PUR Purbond / Loctite adhesive produced by Henkel. Thus, different adhesive products with varying formulations (i.e. viscosity, molecular weight distribution or solids content) and their possible effect on bonding strength were not investigated.

2) Bond performance

It is important to differentiate between the strength and the performance of a bond. Whereas in this study the actual strength of bonded samples was tested in the form of a shear test along the bondline, the performance of the bonds, i.e. the behaviour under severe swelling and shrinking, was not investigated.

## 3. Materials and methods

### 3.1 Materials

#### 3.1.1 Wood

28 green *Eucalyptus grandis* boards (approximately 1500 x 120 x 38 mm, L x W x T) were provided by the Merensky Sawmill in Tzaneen, Limpopo, South Africa. The material was obtained from plantation trees between 20 and 25 years of age. The area where the trees were grown has a sub-tropical climate with an average temperature of 15°C in winter and 28°C during the summer months. Rainfall is predominantly found in mid-summer, between November and March, with an average of approximately 1230 mm per year. The altitude of the plantations ranges from 900 up to 2000 m above sea level (pers. comm. Bruwer, Merensky Forestry Manager, March 2016).

#### 3.1.2 Adhesive

A one-component polyurethane (1C PUR) adhesive, namely “LOCTITE HB S709 PURBOND” (manufactured by Henkel), was employed for this study. According to the manufacturer, the product is formulated on an isocyanate prepolymer basis, with a solids content of 100% and a density of 1160 kg/m$^3$. The particular model “HB S709” has an assembly time of 70 minutes and a curing time of 175 minutes (see figure 2) when applied on dry wood between 8 and 18% MC at climate conditions of 20°C and 65% relative humidity. An adhesive spread rate between 120 and 160 g/m$^2$ is recommended for the standard conditions mentioned above (Henkel 2015).

It needs to be mentioned that although quality assurance testing on wet wood was done successfully by the manufacturer (pers. comm. Ferreira-Netto, Henkel SA, May 2015), a maximum wood MC between 16 and 18% is stated in the technical data sheet. Therefore this type of adhesive was not particularly formulated or recommended for green gluing applications.

### 3.2 Methods

#### 3.2.1 Moisture content and basic density

An approximately 5mm thick slice was cut out of each board with a distance of at least 300 mm from the board’s end. All samples comprised the whole cross section and were free from knots and other defects. Every board was subsequently wrapped in cling film and stored in a cooling chamber at a low temperature of around 2.5°C in order to keep moisture loss to a minimum.

According to the maximum moisture content method for the determination of specific gravity of small wood samples (Smith 1954), every slice was weighed in its green state immediately after cutting *(mass A)*. The samples were subsequently placed underwater in a vertical pressure vessel and weighted in order to stay submerged while several pressure/vacuum cycles between minus 100 kPa

(-1 bar) and 700 kPa (7 bar) were conducted until the wood was completely saturated *(mass B)*. After weighing of the fully saturated samples they were oven dried at 102 ± 3°C to constant oven-dry mass *(mass C)*. All masses were determined to the nearest of 0.1 g.

1) The green MC of the samples was calculated according to SANS 1783-1 (2004):

$$MC_{green} = \frac{A - C}{C} \times 100\%$$

| | | |
|---|---|---|
| $MC_{green}$ = | Moisture content of sample at green state | [%] |
| A = | Weight of sample at green state | [g] |
| C = | Weight of sample at oven-dry state | [g] |

2) The basic density of the samples was determined using the following equation (Smith 1954):

$$Basic\ density = \frac{1}{\frac{B - C}{C} + \frac{1}{1.53}}$$

| | | |
|---|---|---|
| Basic density = | Density of sample at oven-dry state | [$kg/m^3$] |
| B = | Weight of sample at completely saturated state | [g] |
| C = | Weight of sample at oven-dry state | [g] |

1.53 is the average value for the specific gravity of wood cell walls, ranging from 1.50 to 1.56 for different wood species due to variation in chemical composition (Smith 1954).

The results for the 28 samples are listed in table 1. Since the determination of green MC and basic density was a prerequisite for the material selection for this study, the results are displayed here instead of section 4 “Results and discussion”. Each result was assumed to be representative for the whole board from which the sample was taken from.

**Table 1:** Results for green moisture content and basic density samples taken from the 28 *Eucalyptus grandis* boards

| | **Minimum** | **Maximum** | **Average** |
|---|---|---|---|
| **Green MC** [%] | 55.0 | 62.9 | 58.3 |
| **Basic density** [$kg/m^3$] | 435.3 | 574.8 | 519.8 |

### 3.2.2 Experimental design

The aim of this study was to determine the strength of 1C PUR adhesive bonds of edge-glued, green *Eucalyptus grandis* wood. Moreover, to choose certain material and processing variables that are believed to influence the bonding quality and to investigate their interactions with each other. In order to investigate how differences in wood density (basic density), moisture content, adhesive spread rate and pressure impact the bonding strength, a low and a high parameter were assigned to each variable (see table 2).

**Table 2:** Four selected variables, namely wood density, moisture content, adhesive spread rate and pressure together with an assigned low and high parameter each

| | **Low parameter** *(L)* | **High parameter** *(H)* |
|---|---|---|
| **Wood density** [kg/m$^3$] | 440.3 - 488.8 | 560.2 - 574.8 |
| **Moisture content** [%] | 22.6 - 38.2 | 53.7 - 61.2 |
| **Adhesive spread rate** [g/m$^2$] | 150 | 250 |
| **Pressure** [MPa] | 0.6 | 1.0 |

Regarding the adhesive spread rate, the low parameter value *(L)* (150 g/m$^2$) lies within the range recommended by the manufacturer for standard dry-wood applications. A more extreme value was defined for the high parameter *(H)* (250 g/m$^2$) in order to observe the influence of a significantly increased spread rate on the bonding strength. The values for both pressure parameters were either set below (0.6 MPa) or above (1 MPa) of what was assumed to be the appropriate pressure for wet *Eucalyptus grandis* wood in order to emphasize a possible impact of the variable.

A four-by-two (four variables, two parameters each) experimental design was developed, consisting of 16 sample groups, in order to investigate all possible interactions between the four variables (see table 3).

**Table 3:** Four-by-two experimental design, consisting of 16 sample groups with different parameter combinations each

| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Wood density** | *L* | *L* | *L* | *L* | *L* | *L* | *L* | *L* | *H* | *H* | *H* | *H* | *H* | *H* | *H* | *H* |
| **Moisture content** | *L* | *L* | *L* | *L* | *H* | *H* | *H* | *H* | *L* | *L* | *L* | *L* | *H* | *H* | *H* | *H* |
| **Spread rate** | *L* | *L* | *H* | *H* | *L* | *L* | *H* | *H* | *L* | *L* | *H* | *H* | *L* | *L* | *H* | *H* |
| **Pressure** | *L* | *H* | *L* | *H* | *L* | *H* | *L* | *H* | *L* | *H* | *L* | *H* | *L* | *H* | *L* | *H* |

An additional sample group “3-2”, which is not listed in table 3, was produced with the same variable parameters as group 3. However, the wood samples for this group were obtained from another board and therefore had slightly different material properties. This was done in order to examine to what extent the wood material itself is influencing the shear strength results rather than the variable parameters.

### 3.2.3 Sample preparation

For every sample group (1 – 16) the following steps were conducted:

1) The selected board was planed to a thickness of 30 mm.
2) 25 mm wide strips were cut out of the board along the longitudinal direction.
3) Each strip was marked along the longitudinal direction to ensure constant arrangement of year-ring pattern at gluing process (see figure 3 and 4).
4) The 25 mm wide wood strip was cut into 50 mm long pieces.

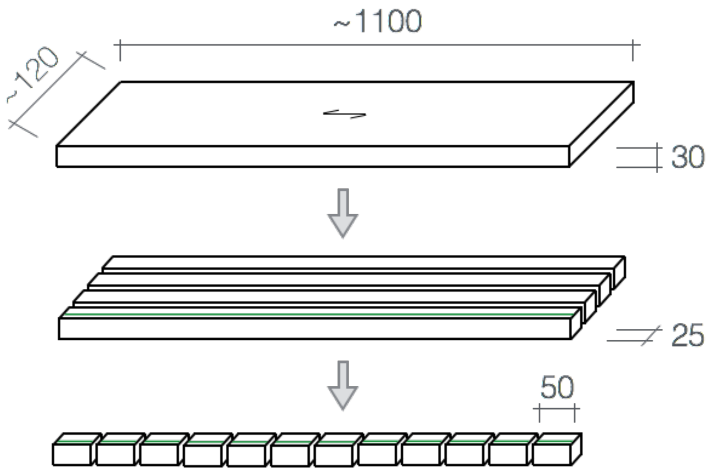


*Figure 3: Illustration of sample preparation for edge gluing, including dimensions in millimetre.*

5) Two pieces from the very end and one piece from the middle section of the strip were collected to re-measure the average MC of the strip, employing the oven-dry method according to SANS 1783-1 (2004). The results thereof are listed in section 3.2.2.
6) Thirteen clear samples (50 x 25 x 30 mm, L x W x T) without knots or other wood defects were glued together immediately after cutting, thus creating 12 bondlines per sample group. Ten bondlines were destructively tested for shear strength determination, leaving two bonds for possible micro CT scans or additional shear strength testing in the case of testing errors.

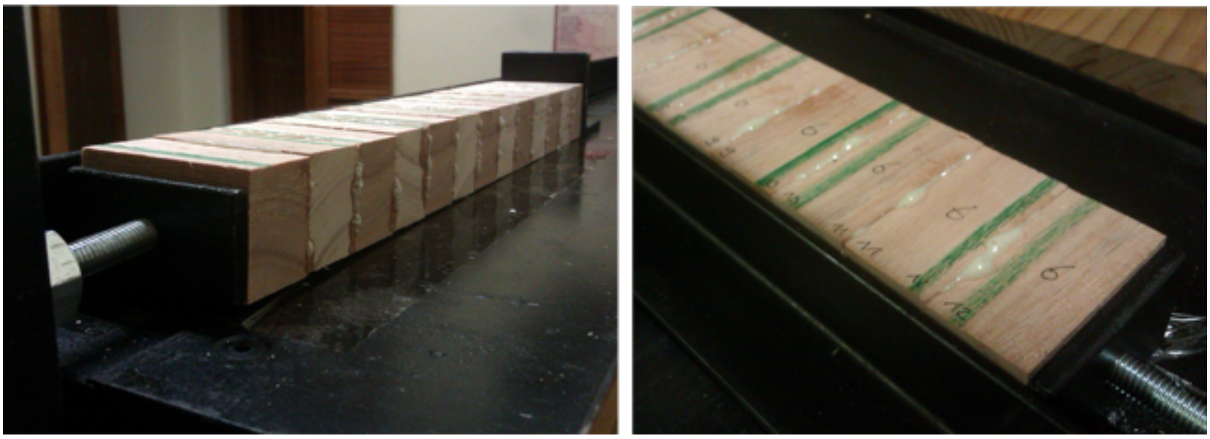

*Figure 4: Gluing of the test bar for sample group 6, showing sample labelling and consistent year-ring arrangement.*

7) The gluing process was conducted in a conditioning room at constant conditions of 20°C and 65% relative humidity. The glued specimens were left in the press device for 20 hours. By strongly increasing the pressing time from recommended 175 minutes for dry-wood applications up to 20 hours, varying press times could be excluded as an additional variable within this study.
8) Afterwards, the bonded samples were stored in a conditioning room until they reached constant mass or equilibrium moisture content. Each sample was marked with the number of the sample group and every bondline was numbered from 1 to 12 (see figure 4).

The sample groups 1 to 8 with a higher MC of roughly 60% were prepared first. The boards intended for the other eight low-MC sample groups were cut and planed to equal dimensions and stored in a conditioning room at 18˚C and 80% relative humidity for a slow moisture loss.

While drying, the boards were weighed in constant intervals and, once close to the theoretical weight calculated for the desired MC, wrapped into cling film and stored for a few more days in order to improve the distribution of the moisture throughout the board. Since the surfaces and end-sections of a piece of lumber dry quicker than the core and middle part, former ones might already be well below FSP. Thus the surfaces may already start to shrink, warp and check, although the theoretical overall MC of a board is above FSP due to the moist core (Dinwoodie 2000). Once the material reached the desired MC, specimens for the sample groups 9 – 16 were prepared as described earlier in this section.

### 3.2.4 Gluing and clamping

To ensure an accurate and constant adhesive spread rate, the glue was applied with 10 ml syringes.

Two custom-made clamping devices, one intended for the low *(L)* and the second one for the high parameter *(H)* sample groups, were used to apply pressure on the samples. The applied pressure was adjusted by positioning the counter weights along the lever arm of each device (distance X, see figure 5).

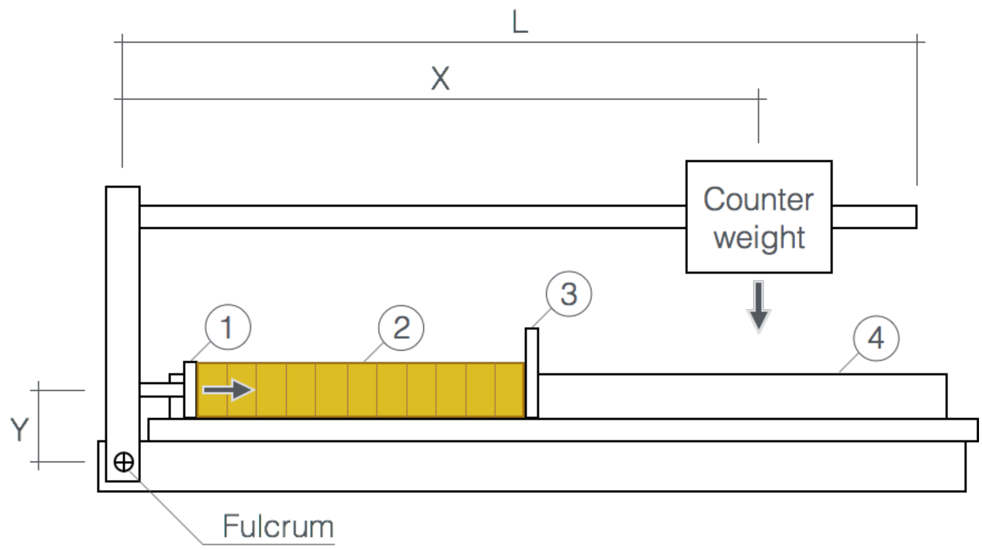


*Figure 5: Side elevation of custom-made clamping device, showing the single elements and distances. Adapted from Perold (2006).*

1 = Pressure plate
2 = Specimens
3 = Stopper
4 = Guide bar
L = Length of lever arm
X = Distance to counter weight centre
Y = Distance between sample centre and fulcrum centre

According to Perold (2006), the exact position of the counter weight along the lever arm can be derived from the following formula:

$$\left(M_{lever\ arm} \times 9.81 \times \frac{L}{2}\right) + \left(M_{counter\ weight} \times 9.81 \times X\right) = (PF \times A \times Y)$$

Hence:

$$X = \frac{(PF \times A \times Y) - \left(M_{lever\ arm} \times 9.81 \times \frac{L}{2}\right)}{(M_{counter\ weight} \times 9.81)}$$

| | | |
|---|---|---|
| X = | Distance to counter weight centre | [m] |
| PF = | Desired pressure | [Pa] |
| A = | Gluing area | [$m^2$] |
| Y = | Distance between sample centre and fulcrum centre | [m] |
| $M_{lever\ arm}$ = | Weight of lever arm | [kg] |
| 9.81 = | Earth's gravitational pull | [m/s] |
| L/2 = | Centre of lever arm length | [m] |
| $M_{counter\ weight}$ = | Weight of counter weight | [kg] |

Since the dimensions and consequently the weight of the single components of both clamping devices varied slightly, the positions of the counter weights was calculated for both of them separately.

### 3.2.5 Shear strength testing

After reaching EMC, the glued samples (one test bar per sample group) showed slight deformation due to moisture loss below FSP and as a consequence shrinkage of the wood material. The test samples, containing one bondline each, were therefore cut out of the test bars in longitudinal direction. Each sample was processed to ensure that both cross sections (top and bottom) were perpendicular to the bondline so that the pressure from the shear device could be applied exactly on and along the bondline. Before the samples were tested, the glued area *(A)* of every sample was measured with a sliding gauge and determined to the nearest of 0.5 mm.

Ten specimens per sample group were examined with a shear test according to EN 16351 (2015):

1) Pressure was applied from the top on the cross-section of the sample along the grain direction and with the shearing tool in-line with the bondline (see figure 6).
2) Loading was increased at a constant rate of 3 mm/min until failure of specimen.
3) The ultimate load *($F_u$)* at the time of failure was recorded.

4) The shear strength *($f_v$)* for each specimen was calculated with the following formula:

$$f_v = \frac{F_u}{A}$$

| | | |
|---|---|---|
| $f_v$ = | Shear strength of tested sample | [$N/mm^2$] |
| $F_u$ = | Ultimate load applied on tested sample | [N] |
| A = | Sheared area (glued area) of tested sample | [$mm^2$] |

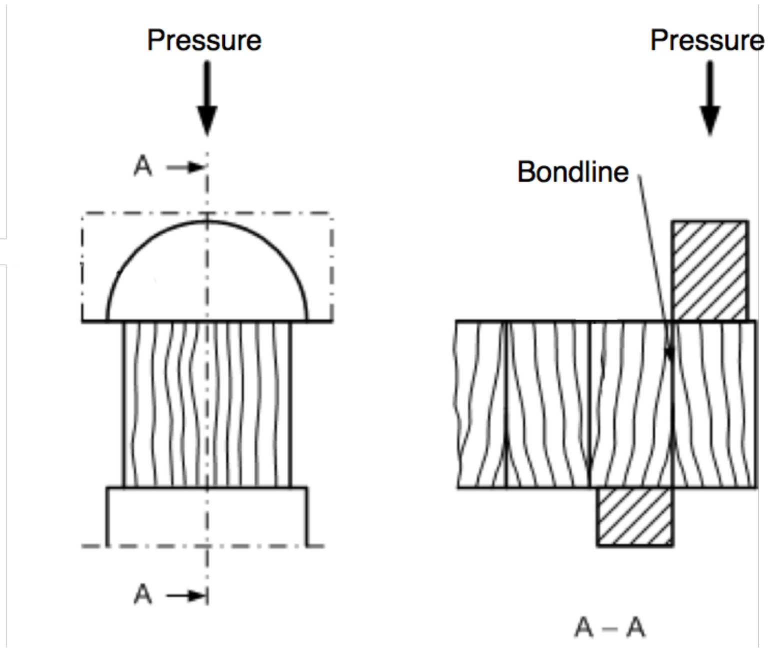


*Figure 6: Illustration of shear test setup, showing sample loaded at the end-grain in-line with the bondline. Adapted from EN 16351 (2015).*

### 3.2.6 Additional testing

1) Adhesive penetration (micro CT)

Two samples with extreme shear strength results were further investigated regarding the adhesive penetration into the wood cell structure. To be able to observe the full pathway of the glue, a micro CT scanner (General Electric Phoenix Nanotom S) was employed in order to create three-dimensional, high resolution images of selected areas around the bondline.

2) Heartwood detection

In order to determine the heartwood-sapwood ratio of the tested samples, a heartwood detection test was conducted according to SANS 6000 (2004). Therefore a dimethyl yellow-dye and ethanol reagent was applied on the cross-sections of the shear strength specimens. Due to the occurring difference in colour between heartwood (becomes red) and sapwood (remains yellow) after application of the mixture, it could be determined that all the utilised material was composed of exclusively *Eucalyptus grandis* heartwood.

### 3.2.7 Statistical analysis

The Statistica 13 software was employed to verify that the obtained data fulfilled the assumptions of normal distribution and homogeneity of variance before performing a factorial design analysis of variance (ANOVA) on the test results in order to determine how the different variables influence the shear strength of the bonded samples. The analysis was performed on all 17 sample groups, including the additional group 3-2.

The WFP of every sample was estimated to the nearest of 5%. A linear regression model was created to determine if a statistically significant correlation exists between shear strength and WFP of the samples.

## 4. Results and discussion

The quality of 1C PUR adhesive bonds on green edge-glued *Eucalyptus grandis* wood was assessed on the basis of a shear test along the bondline. An overview of the test results of the 17 sample groups is given in the form of a boxplot diagram in figure 7, together with the obtained results in table 4.

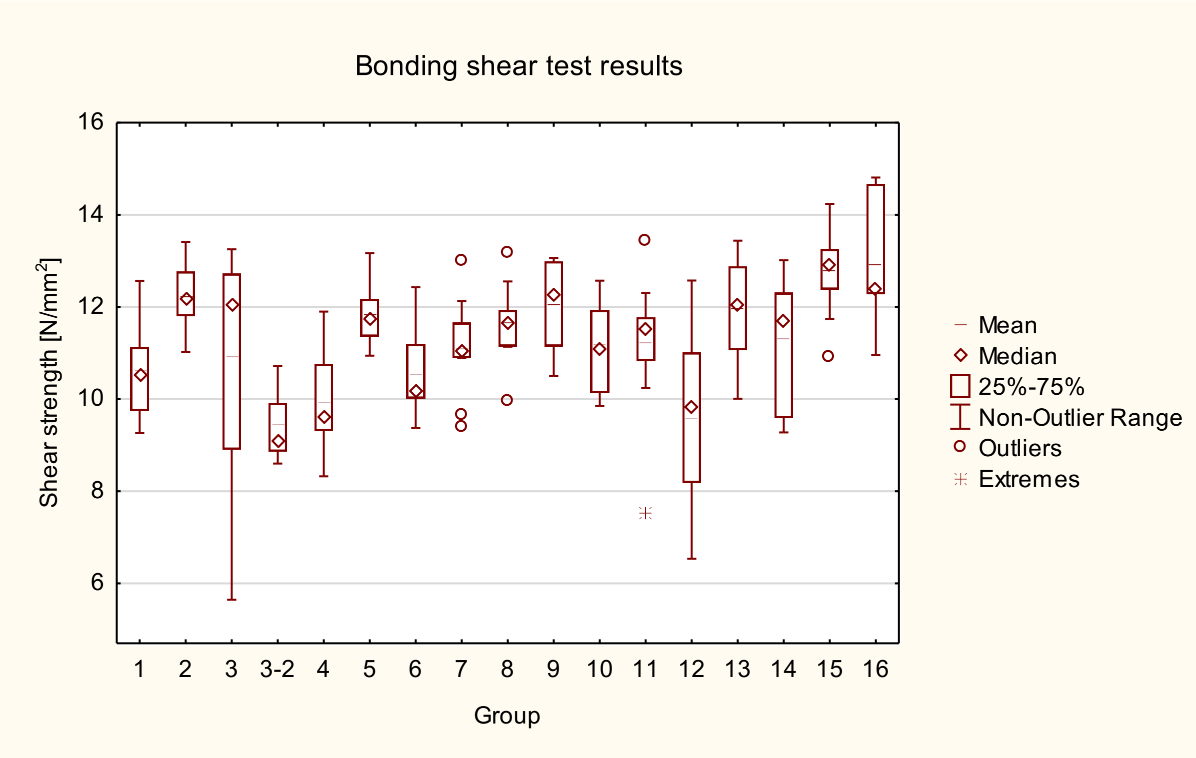


*Figure 7: Boxplot diagram showing shear test results for all 17 sample groups.*

**Table 4:** Shear test results for all 17 groups, showing minimum, maximum, mean and standard deviation values in N/mm$^2$, including summary of test results

| | 1 | 2 | 3 | 3-2 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|---|
| **Min.** | 9.3 | 11.0 | 5.6 | 8.6 | 8.3 | 10.9 | 9.4 | 9.4 | 9.9 |
| **Max.** | 12.6 | 13.4 | 13.3 | 10.7 | 11.9 | 13.2 | 12.4 | 13.0 | 13.2 |
| **Mean** | 10.6 | 12.2 | 10.9 | 9.4 | 9.9 | 11.8 | 10.5 | 11.1 | 11.7 |
| **St. dev.** | 1.1 | 0.7 | 2.5 | 0.8 | 1.2 | 0.7 | 0.9 | 1.1 | 0.9 |

| | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | Summary |
|---|---|---|---|---|---|---|---|---|---|
| **Min.** | 10.5 | 9.9 | 7.5 | 6.5 | 10.0 | 9.3 | 10.9 | 11.0 | **5.6** |
| **Max.** | 13.1 | 12.6 | 13.4 | 12.6 | 13.4 | 13.3 | 14.2 | 14.8 | **14.8** |
| **Mean** | 12.1 | 11.2 | 11.2 | 9.6 | 12.0 | 11.3 | 12.8 | 12.9 | **11.2** |
| **St. dev.** | 1.0 | 1.0 | 1.5 | 2.1 | 1.1 | 1.4 | 1.0 | 1.4 | **1.6** |

Shear strength values between 5.6 and 14.8 N/mm$^2$, with an average of 11.2 N/mm$^2$, were obtained for all 170 tested samples. Thus all specimens exceeded the minimum required characteristic shear strength of 3.5 N/mm$^2$ for edge-bonds according to EN 16351 (2015).

Sample group 16 showed the best shear strength results with values ranging from 11.0 to 14.8 N/mm$^2$ and a mean of 12.9 N/mm$^2$. Group 3 on the other hand produced the sample with the lowest test result (5.6 N/mm$^2$) but otherwise showed a mean value (10.9 N/mm$^2$) close to average and a good maximum result of 13.3 N/mm$^2$. The strong variation in results is also reflected by the standard deviation of group 3, which was the highest of all sample groups (2.5 N/mm$^2$). In comparison, group 3-2 exhibited the lowest mean value of all groups (9.4 N/mm$^2$) with much denser scattering of test results and thus a comparably small standard deviation of 0.8 N/mm$^2$.

A parametric Welch two-sample test and a non-parametric two-sample Wilcoxon rank sum test were performed in order to determine if the test results of the two sample groups 3 and 3-2, which were produced with equal variable parameters but from different *Eucalyptus grandis* boards, statistically differ at a 5% significance level. Since both tests showed a p-value of 0.11 it can be concluded that the inevitable use of different *Eucalyptus grandis* boards, and the consequent variations in material properties, would have no significant influence on the test results of this study.

A factorial design ANOVA was carried out on the test results in order to determine how the different variables wood density, moisture content, adhesive spread rate and pressure as well as the interactions among them, influence the shear strength of the bonded samples. Two three-way interactions (see figure 8 and 10) were found to be significant and used as the centre point of investigation.

**Table 5:** ANOVA table showing the significance of wood density, moisture content, pressure and adhesive spread rate for the shear strength of edge-glued *Eucalyptus grandis* samples

| Effect | SS | Degr. of Freedom | MS | F | p |
|---|---|---|---|---|---|
| Intercept | 21135.99 | 1 | 21135.99 | 12300.52 | 0.000000 |
| {1}Density | 15.40 | 1 | 15.40 | 8.96 | 0.003215 |
| {2}MC | 33.08 | 1 | 33.08 | 19.25 | 0.000021 |
| {3}Pressure | 3.76 | 1 | 3.76 | 2.19 | 0.140933 |
| {4}Spreadrate | 3.62 | 1 | 3.62 | 2.11 | 0.148670 |
| Density*MC | 4.76 | 1 | 4.76 | 2.77 | 0.098023 |
| Density*Pressure | 8.68 | 1 | 8.68 | 5.05 | 0.026019 |
| MC*Pressure | 0.01 | 1 | 0.01 | 0.01 | 0.935832 |
| Density*Spreadrate | 3.44 | 1 | 3.44 | 2.00 | 0.159014 |
| MC*Spreadrate | 41.73 | 1 | 41.73 | 24.28 | 0.000002 |
| Pressure*Spreadrate | 0.00 | 1 | 0.00 | 0.00 | 0.970374 |
| Density*MC*Pressure | 10.82 | 1 | 10.82 | 6.30 | 0.013128 |
| Density*MC*Spreadrate | 1.77 | 1 | 1.77 | 1.03 | 0.311982 |
| Density*Pressure*Spreadrate | 0.01 | 1 | 0.01 | 0.00 | 0.954903 |
| MC*Pressure*Spreadrate | 17.90 | 1 | 17.90 | 10.42 | 0.001527 |
| Density*MC*Pressure*Spreadrate | 3.10 | 1 | 3.10 | 1.81 | 0.180962 |
| Error | 264.62 | 154 | 1.72 | | |

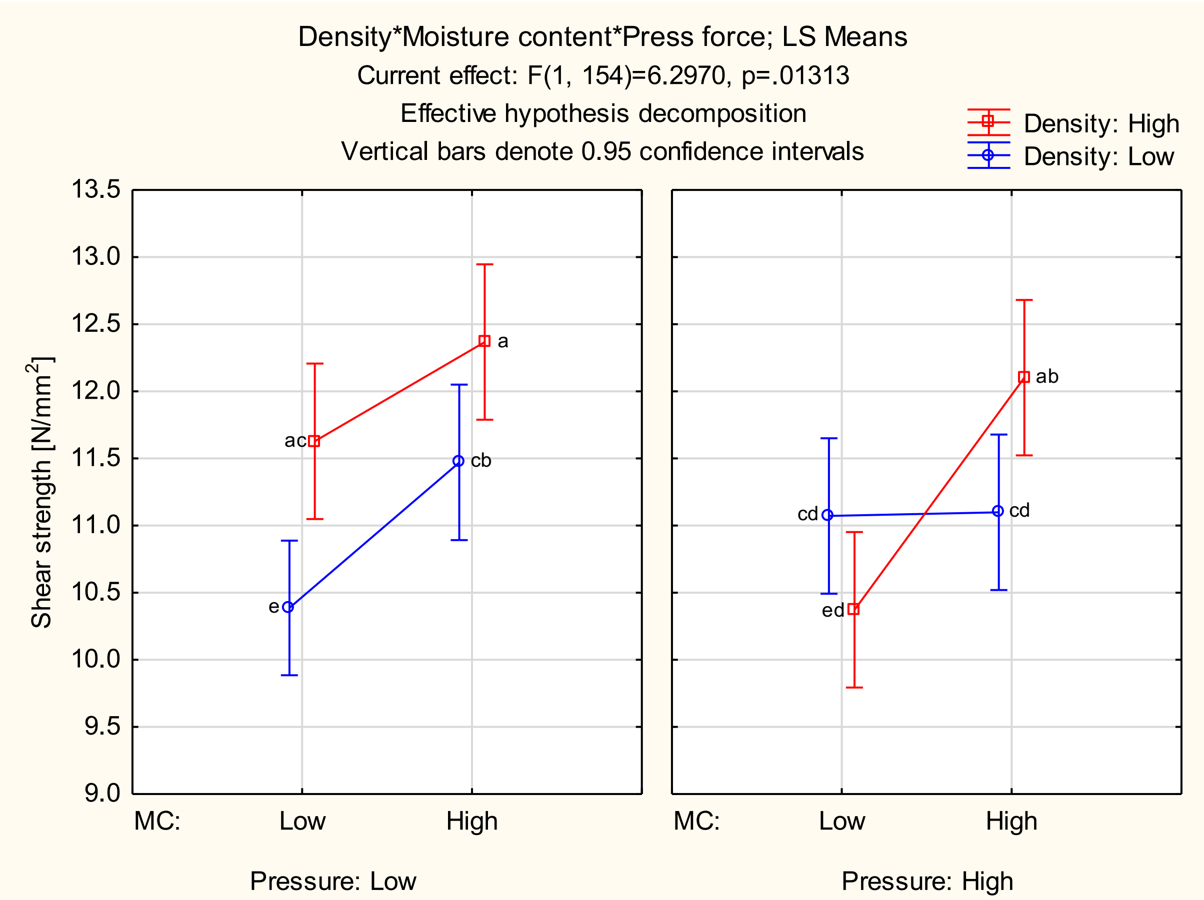


*Figure 8: Significant three-way interaction between wood density, moisture content and pressure for the shear strength of edge-bonded Eucalyptus grandis samples.*

The interaction between wood density, moisture content and pressure turned out to be statistically significant at a 5% significance level with a p-value of 0.013.

All trendlines show either improved or at least equally good results for higher MC samples. This can be explained by the fact that the utilised 1C PUR adhesive is moisture-curing and for that reason prefers a higher availability of water (Weaver and Owen 1995). Wood is also known to become softer and more flexible with increasing MC. This makes it easier for the two wood substrates to adapt to each other under pressure and thus more likely to form a high-quality glueline without cavities and stress concentrations (Simpson 1999, Sterley 2012).

Another possible explanation is on the basis of the Dent theory (Dent 1977). The surface sorption model (figure 9) postulates that once the cell walls are completely saturated, the free water in the cell lumina forms a film on the cell wall surface. The so-called "primary layer" (S1) consists of water molecules, which are strongly attached to the sorption site (S0). As the next layers of "secondary" water molecules (or another fluid) (S2, S3, etc.) add on top of either primary or other secondary water molecules, much less binding energy exists between them (Time 1998). This allows enhanced adhesive penetration as the forces between the fluid resin and the water film are weaker than between the adhesive and the dry cell wall surface.

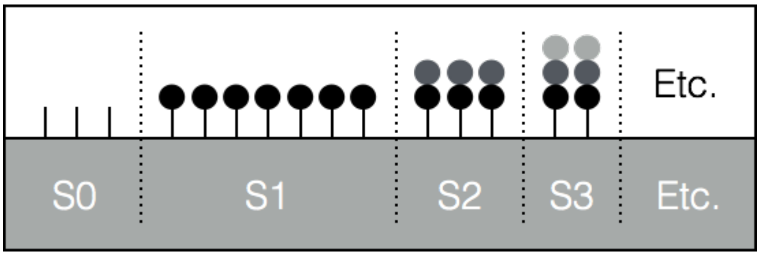


*Figure 9: Surface sorption model, showing the sorption site S0, the "primary layer" S1 and the "secondary layers" S2, S3, etc. Adapted from Dent (1977).*

The better shear strength results for high-density samples over low-density samples displayed in figure 8 (left graph) might be explained by the fact that the mechanical properties (viz. strength) generally increase with increasing density and the majority of the shear test samples failed in the wood instead of on the glueline (Frihart and Hunt 2010).

When higher pressure (1.0 MPa) was applied (figure 8, right graph), high MC samples (60%) showed the same results as for the lower pressure (0.6 MPa). However, for samples with lower MC around FSP the results increased for low-density and decreased for high-density samples. A reason for that could be the penetration behaviour of the adhesive. Since low-density wood usually shows an increased amount of vessel elements, more glue can be absorbed by the wood structure as compared to samples with a higher density. An increased pressure can therefore lead to a deeper adhesive penetration into low-density wood, consequently improving the bonding strength due to an increased surface contact (Lehringer and Gabriel 2014). For high-density timber on the other hand it tends to cause an adhesive squeeze-out (Sterley 2012), especially if the wood surface is below FSP and thus too dry to create the earlier described "primary water layer" (figure 9) on the cell walls for enhanced conduction of the adhesive into the wood structure. However, since with 0.6 and 1.0 MPa two "extreme" pressure parameters were investigated, it might be that the best results could be achieved for a value in between.

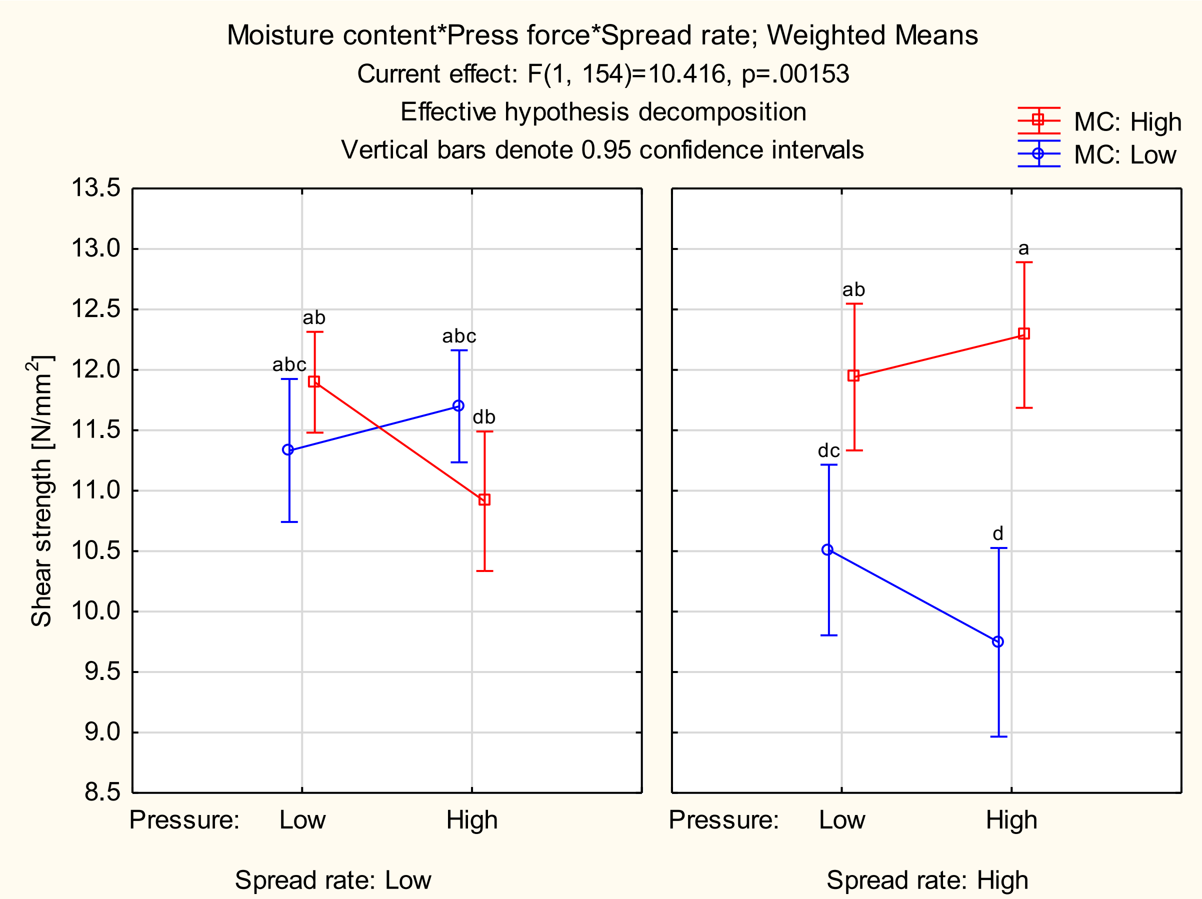


*Figure 10: Significant three-way interaction between moisture content, pressure and spread rate for the shear strength of edge-bonded Eucalyptus grandis samples.*

With a p-value of 0.0015, the three-way interaction of moisture content, pressure and adhesive spread rate was statistically highly significant. Since the Levene's test (equality of variances) turned out to be significant at a level of 0.01 (<1%), a weighted means graph was generated. Although giving similar results to the least-squares means, the more conservative weighted means version is reported here.

No significant difference in shear strength was obtained for the low adhesive spread rate (150 g/m$^2$) and the two parameters of MC and pressure (figure 10, left graph). When a higher amount of adhesive was applied (250 g/m$^2$) the test results for high MC samples turned out to be significantly better than the samples at FSP. This trend increased with increasing pressure (figure 10, right graph). The fact that the best as well as the worst result in this three-way interaction were both obtained for the combination of a high spread rate and high pressure, but with differing levels of MC, indicates that the availability of water in the wood had a great impact on the bonding strength. The reason for that is likely to be the water layer (figure 9), which forms on the cell wall surface of wood above FSP and thus allows enhanced penetration. Together with a high pressure more adhesive can thus be forced into the wood structure instead of being pressed out of the glueline, as it was the case for samples with a lower MC.

For the green edge-glued *Eucalyptus grandis* samples with a MC clearly above FSP, the best shear strength results were achieved with a high adhesive spread rate together with a high pressure. However, since in an industrial environment the MC during the processing stage of green-glued materials usually varies and is difficult to control, a lower spread rate might be the safer option due to less variation in bonding strength, especially in the case of wood with a lower MC around FSP. A lower adhesive spread rate will obviously also be more preferable for timber processors from an economic perspective. Since with 150 and 250 g/m$^2$ two strongly differing adhesive spread rates were investigated, it is advisable to also investigate how other amounts in between these two values would perform.

In order to determine if a statistically significant correlation exists between the shear strength and the WFP of the samples, a linear regression model was fit on the data of the test results (figure 11). The correlation turned out to be highly significant, with a p-value of below 0.0001. The analysis exhibited that the WFP of the samples increased with an increasing shear strength. This is probably since a high-quality bondline is stronger than the wood itself and thus causes a bigger part of the failure in the wood material, whereas specimens with poor bonding failed to a greater extent on the glueline. Consequently the obtained shear strength results do not represent the maximum strength of the adhesive but rather the strength properties of the wood of the samples.

According to the linear regression the WFP with regard to the shear strength can be calculated as follows:

$$Wood\ Failure\ Percentage\ [\%] = 48.6839 + (3.2243\ x\ shear\ strength\ [N/mm^2])$$

However, with a R-squared value of only 0.115, the goodness-of-fit for this model was fairly low. This means that the fitted regression line explains only 11.5% of the variation in results and thus makes predictions with the above stated equation inaccurate.

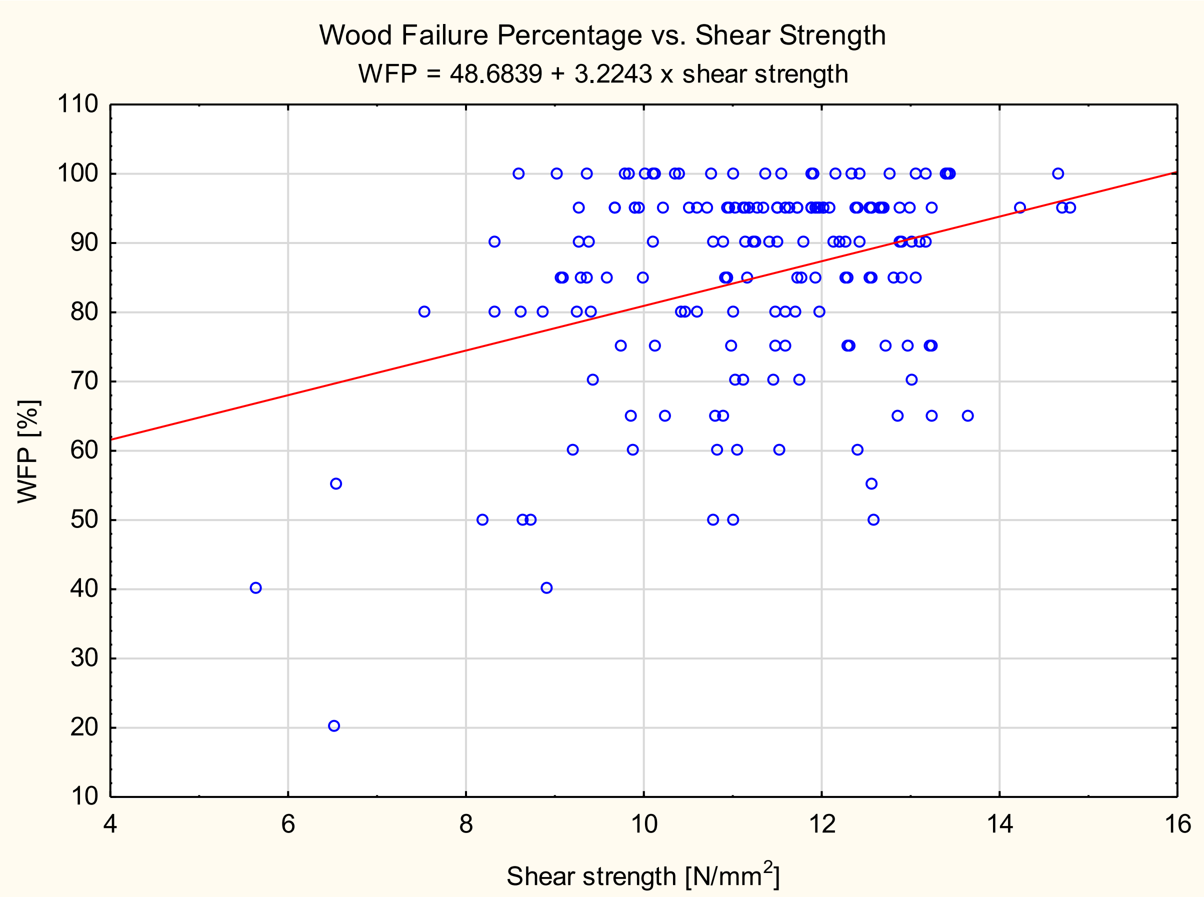


*Figure 11: Linear model of WFP vs. shear strength of green edge-glued Eucalyptus grandis samples, showing fitted linear regression line and equation.*

A micro CT scanner was employed in order to investigate the penetration behaviour of 1C PUR adhesive into *Eucalyptus grandis* wood on the basis of two shear test samples, one with a very good (group 16) and one with a comparably poor result (group 12). Therefore a small piece of wood, about 4 mm in length (longitudinal direction) and with a diameter of roughly 3 mm (cross section, including the bondline) was cut from both samples and shaped into a tubular form.

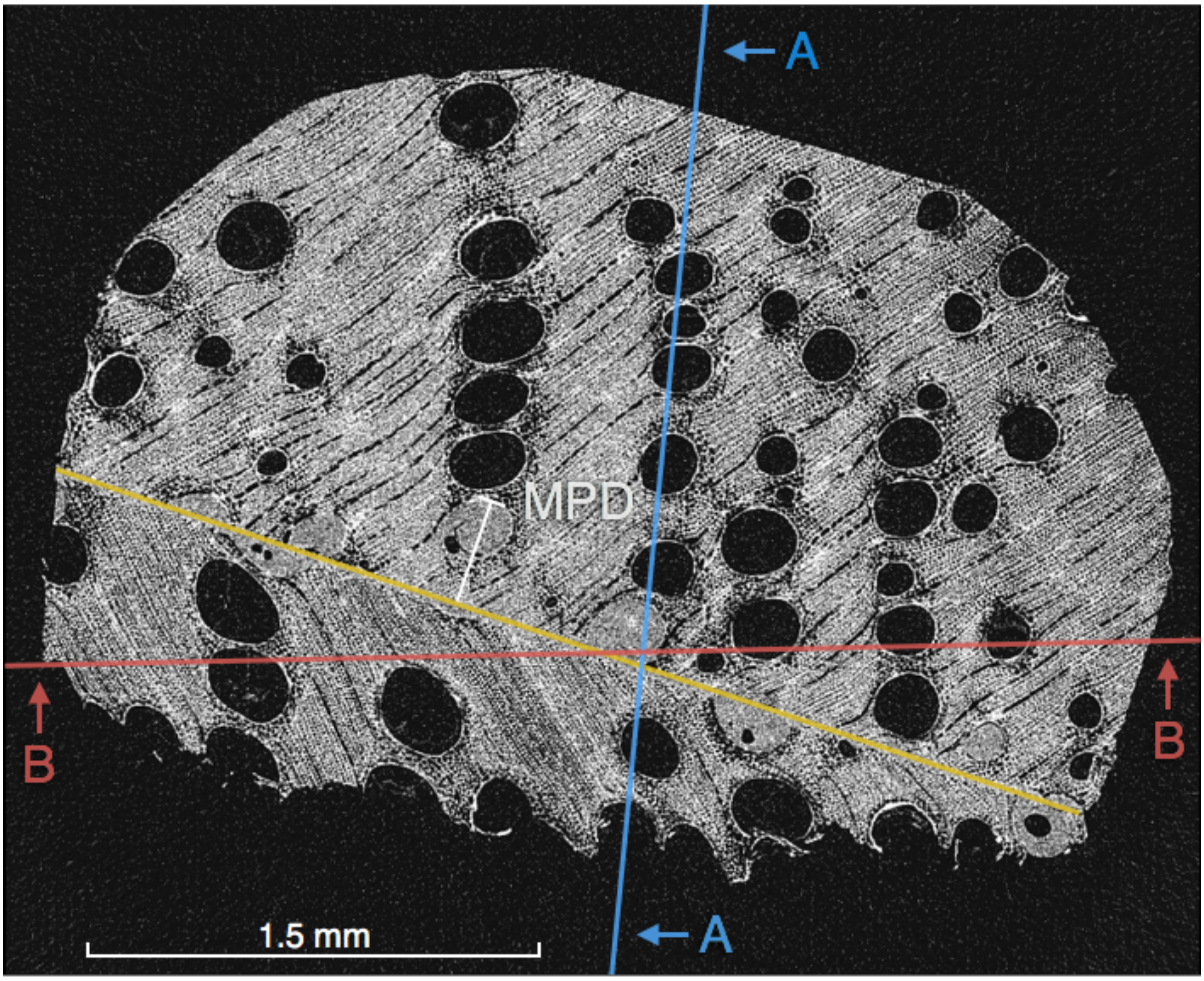


*Figure 12: Micro CT scan of cross section of high shear strength sample (group 16) with highlighted bondline (yellow) and drawn lines for A-A (blue) and B-B (red) longitudinal sections.*

The first scan was carried out on a sample taken from specimen 16-9 (sample group 16, bondline 9), which showed the highest shear strength of all test samples (14.8 N/mm$^2$). In this case the sample failed in the wood structure along vessel elements instead of on the glueline as can be seen on the bottom part of figure 12. The dimensions of the scanned cross section are approximately 3.6 x 2.5 mm, whereas the scans of the longitudinal sections (figure 13) covered 3.3 mm in length along the bondline. The bondline in figure 12 (indicated yellow) had a length of 3.6 mm and a thickness between 0.02 and 0.03 mm. Vessel diameters were ranging from 0.05 to 0.31 mm with 0.17 mm on average.

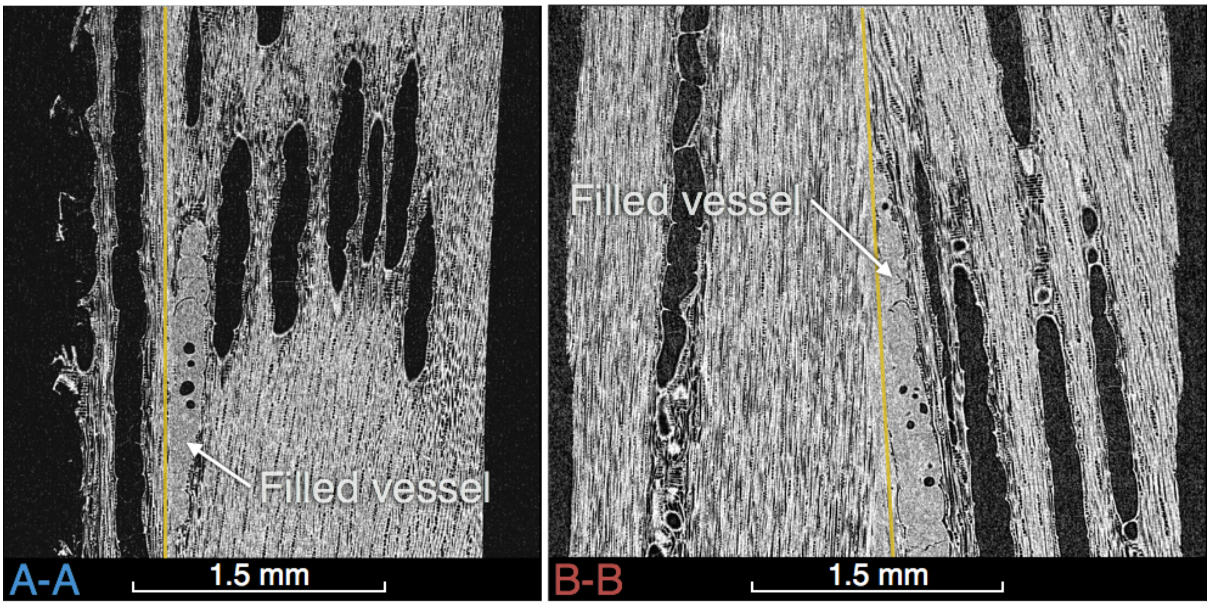


*Figure 13: Micro CT scans of both longitudinal sections A-A (left, blue) and B-B (right, red) with highlighted bondline (yellow) and indicated adhesive-filled vessels.*

Both scans of the longitudinal sections show that penetration into the wood structure took place through those vessel elements which were in direct contact with the glueline, whereas adjacent vessels that were neither connected to a filled vessel nor the glueline remained empty (figure 13). The widest distance between the glueline and an adhesive-filled vessel (maximum penetration depth, *MPD*) for this sample was measured as 0.47 mm (figure 12).

In order to compare the first scan with a sample of lower bonding quality, another micro CT specimen was prepared from shear test sample 12-1 (sample group 12, bondline 1). This specimen failed on the glueline, which can be seen in the top part of figure 14, and had a comparably low shear strength of 6.5 N/mm$^2$. Although group 3 produced the lowest test result, a sample from group 12 was preferred as it differed in only one variable parameter (lower MC) from sample group 16.

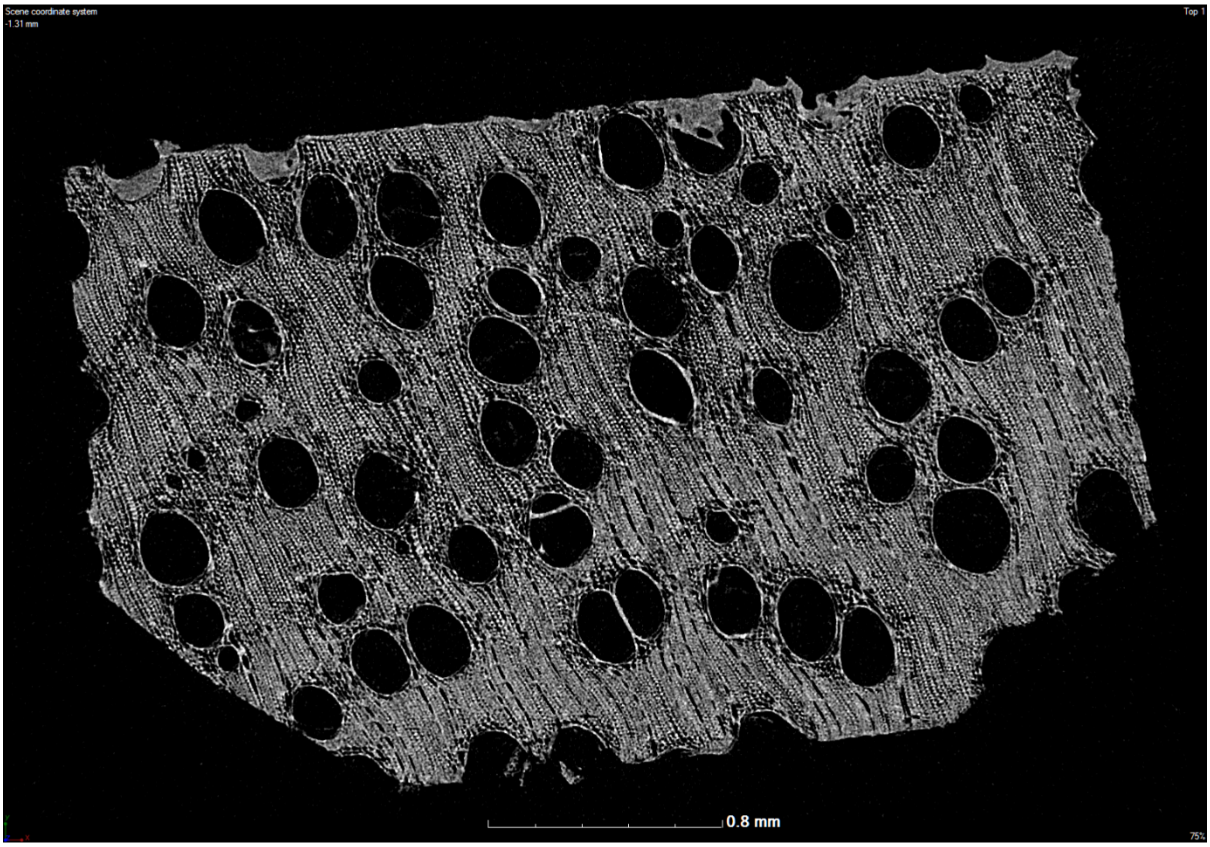


*Figure 14: Micro CT scan of cross section of low shear strength sample (12-1), showing glueline failure.*

The dimensions of the scanned cross section displayed in figure 14 are approximately 3.6 x 2.25 mm. The bondline had a length of 3.5 mm with a varying thickness between 0.01 and 0.06 mm. This variation is probably because the shear failure took place in the glueline and therefore some parts of the adhesive layer were strechted as the other substrate was ripped away. The vessel diameters were ranging from 0.09 to 0.32 mm with a mean value of 0.22 mm. Like in the first sample, only vessels in direct contact with the glueline were filled with adhesive. Although in this case, the vessel elements contained markedly less adhesive compared to the first sample with the higher bonding strength. Consequently a lower maximum penetration depth of 0.3 mm was measured.

The variable parameters of the two sample groups 12 and 16 differed only in MC. Both samples were of high density (>550 kg/$m^3$) and were bonded with a 250 g/$m^2$ adhesive spread rate under the pressure of 1.0 MPa. This shows that an elevated MC facilitates penetration and together with a high pressure allows a deeper flow of the glue into the wood structure (sample 16-9, figures 12 and 13) as compared to wood with a surface below FSP.

However, it also has to be mentioned that a micro CT scan can only display a small part (roughly 4 x 4 mm) of the total gluing area (50 x 30 mm) and therefore is not representative for the whole sample. Furthermore, the low bonding strength of the second specimen (12-1) might not merely be explained by the reduced penetration of the adhesives but also by the fact that wood samples around FSP are likely to have a drier surface, which start to shrink and warp and thus create uneven substrates, which can lead to cavities and stress concentrations within the glueline (Simpson 1999).

The question if the 1C PUR adhesive could penetrate into the *Eucalyptus grandis* wood only by the way of vessels or as well through the pits of interconnected fibres could not be satisfactorily answered. Although all samples were determined as heartwood material, which is known for its low permeability due to blocked cells and pits (Dinwoodie 2000), the possibility of penetration through fibres and rays could not be completely ruled out as even the strongly magnified micro CT images were not able to provide a clear enough view on the lumina of these very small cells (figure 15). The fact that the lumina of the fibres next to the glueline can be observed means that there was definitely no complete penetration of adhesive into these fibres. However, it could be that some parts of what seems to be the glueline might be fibres filled with adhesive and hence there was not sufficient evidence to suggest the adhesive did or did not penetrate into the fibres.

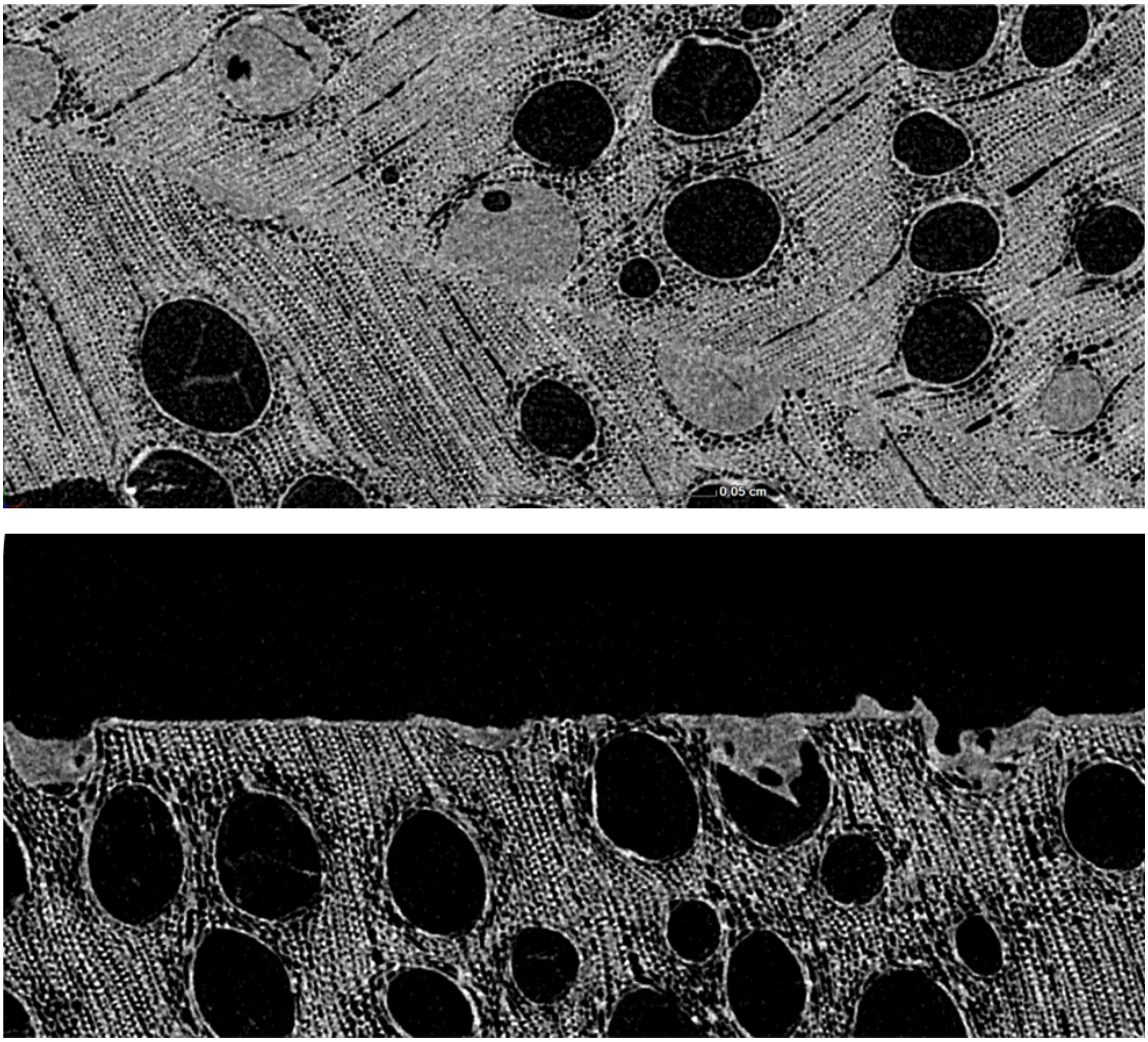


*Figure 15: Magnified view of bondlines and surrounding wood structure of both samples (16-9 and 12-1) scanned with micro CT scanner.*

## 5. Conclusions and recommendations

The green edge-glued *Eucalyptus grandis* samples tested in this study showed high shear strength values clearly exceeding the minimum requirements for CLT production as specified in the EN 16351 (2015) document. Better or at least equally good results (depending on combination of variable parameters) were achieved for the specimens with a higher MC of roughly 60% compared to the low-MC samples around FSP. The sample group with the combination of high wood density, high MC, high adhesive spread rate and high pressure performed superior to all other groups. It seemed like a higher amount of adhesive can perform significantly better with an increased MC clearly above FSP. If both a high MC and a high spread rate are given, an increased pressure would result in very good shear strength values, whereas for wood around FSP a lower adhesive spread rate gave more stable results.

A statistically significant correlation between shear strength and WFP was obtained, showing that the WFP of the green-glued samples increased with increasing shear strength.

Adhesive penetration into the wood cell structure could be observed exclusively by the way of vessel elements which were in direct contact with the bondline, with a higher penetration depth for the sample of superior bonding quality. Other cell types were too small to determine whether or not they were containing adhesive in their lumina.

It is recommended that additional testing is carried out with an adhesive spread rate of 200 $g/m^2$ and 0.8 MPa pressure in order to investigate the bonding quality with less “extreme” parameters for these two variables. However, since all samples exceeded the minimum requirements regarding bonding strength, manufacturers of green-glued products may employ a lower adhesive spread rate for economic reasons and thus further investigation concerning different press times should be conducted. In order to determine how 1C PUR bondlines in combination with *Eucalyptus grandis* wood will behave under long-term conditions, i.e. severe shrinking and swelling, an additional delamination test should be performed as this study was only focused on the strength of the bond rather than its performance. In the case of further research on this topic it is also recommended to introduce dry-glued control specimens in order to compare the quality of the green-glued material as well as an increased sample size, as it would help to obtain more accurate and meaningful results by minimising the variation due to material properties. Furthermore, another tool than the micro CT scanner may be considered for the investigation of adhesive penetration into *Eucalyptus grandis* wood, which should include not only heartwood but the more permeable sapwood as well.

A shortened version of the content of this chapter was created in the format of a scientific paper to be submitted to an academic journal. At the time this thesis was finalised the paper was unpublished.

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# Chapter 3.
# The potential of edge gluing of green *Eucalyptus grandis* lumber to inhibit the development of certain wood defects during kiln drying

## 1. Introduction

In South Africa only about 1% of the total land area is used for commercial forestry. These approximately 1.27 million ha of forest plantations are mostly composed of *Pinus* (51%) and *Eucalyptus* (40%) species (DAFF 2012, DAFF 2015). Over the past twenty years afforestation in the country has declined. This was mainly due to a scarcity of suitable land and restrictions on expanding plantation areas, as new regulations regarding water usage were introduced by the government. At the same time the amount of hectares used for short-rotation production, i.e. pulpwood purposes, increased markedly (Chamberlain et al. 2005, DAFF 2015). Since the demand for roundwood is steadily growing, but afforestation is stagnating, a shortage of softwood lumber is expected within the next two decades (Crickmay et al. 2005). Consequently South Africa may become a net importer of softwood sawn timber. That in turn would have a negative impact on many forestry subsectors, which are considered very important for the socio-economic stability of the country (DAFF 2015).

A possible solution to meet the growing needs for timber could be the utilisation of hardwood species of which the vast majority is currently used for pulp and paper products and wood chips. This would not only add more value to the product but also create additional employment possibilities within the country due to an increased labour intensity compared to the pulp sector (DAFF 2012). With approximately 270 000 ha of plantation area, the fast-growing *Eucalyptus grandis* is the predominant hardwood species in South Africa (DWAF 2009). Unseasoned and finger-jointed *Eucalyptus grandis* sawn timber of different age-classes between 5 and 18 years was investigated by Crafford (2013). Although good results were obtained for strength and stiffness, the requirements for sawn wood according to the SANS 1783-2 (2004) could not be met as the test boards exceeded the maximum values for twist and checking. Since most wood defects either originate or aggravate during the drying stage, the edge gluing of several sawn, wet *Eucalyptus grandis* boards before kiln drying was considered to inhibit deformation and thus to reduce the development of so-called “drying defects”.

In order to investigate the feasibility of edge gluing green *Eucalyptus grandis* wood and to determine how different material and processing variables influence the bonding strength, a preliminary study on small size specimens was conducted by the author (see chapter 2). This investigation exhibited good shear strength results for the assessed one-component polyurethane (1C PUR) bondlines and provided information regarding the appropriate adhesive spread rate and clamping pressure with respect to varying wood densities and moisture contents. With this knowledge being available, investigations could be carried out on industrial size lumber samples.

In order to determine if the edge-bonding of green, sawn boards can contribute to reduce the development of various wood defects during kiln drying, a process similar to EGAR (edge-glue-and-rip, Bergman et al. 2010) was developed. Therefore edge-bonded panels were produced from wet material and once dried to target MC ripped apart into single boards, which were compared to sawn boards of the same dimensions without being edge-glued prior to kiln drying. Although this project was focused on the evaluation of green edge gluing for the minimisation of defects in structural lumber, the possible potential of the edge-bonded panels for the manufacturing of mass timber products such as cross-laminated timber (CLT) or other panel-type products is also a possibility, as the manufacturing of panels is in any event part of the process.

The objective of this study was to investigate how the age of the timber, the presence of pith, finger jointing, edge gluing, and stress-relieve grooves of green *Eucalyptus grandis* boards influence the development of certain wood defects, namely check, split and warp in the form of bow, cup and twist.

## 2. Literature review

### 2.1 Eucalyptus grandis

*Eucalyptus grandis* is a tall, fast-growing hardwood species from the *Myrtaceae* family. Originally from Australia, the species was introduced in South Africa around 1885 and at present, with almost 300 000 ha of plantations, is the predominant hardwood species in the country (DWAF 2009, Orwa et al. 2009, DAFF 2015). An exceptionally high growth rate of 20 to 30 $m^3$/ha/year, together with other favourable properties, such as the excellent shape of trunk and high strength values make *Eucalyptus grandis* the most commercially planted eucalypt worldwide among more than 600 different *Eucalyptus* species (Sánchez Acosta et al. 2008, McMahon et al. 2010).

In South Africa *Eucalyptus* trees can be found up to an altitude of 2 700 m and are able to grow within a temperature range from -1 to 40 ˚C and 100 up to 1 800 mm mean annual rainfall (Orwa et al. 2009). Industrially used *Eucalyptus grandis* trees are almost exclusively cultivated on commercial plantations, of which about 82% in South Africa are certified by the Forest Stewardship Council (FSC) (DAFF 2012). According to DAFF (2015), *Eucalyptus* plantations amount to about 527 300 ha, with *Eucalyptus grandis* making up almost half (47.9%) of the total hardwood area in the country. By 2013 the majority of *Eucalyptus grandis* trees was between 0 and 10 years old, with a significant increase of *Eucalyptus grandis* based cloned hardwood species planted over the recent years.

Although *Eucalyptus grandis* was initially introduced for mining timber and paper production, various products like flooring, furniture and other internal applications were produced from the wood since then (McMahon et al. 2010). Between 2012 and 2013 the majority of the *Eucalyptus grandis* plantation area was intended for pulpwood production (219 267 ha, 73%), followed by mining timber (46 294 ha, 16%), poles (17 841 ha, 6%) and sawlogs (13 816 ha, 5%) (DAFF 2015). However, recent research showed that air-dried *Eucalyptus grandis* lumber could not comply with the South African national standard for sawn eucalyptus timber SANS 1707-1 (2010). This was mainly due to the low dimensional stability of the lumber, which caused extensive warp and cracking of the wood material (Crafford 2013).

### 2.2 One-component polyurethane adhesives

Over the last two decades one-component polyurethane (1C PUR) adhesives gained in importance for the industrial manufacturing of engineered wood products, especially for load bearing lumber, such as glulam, finger-jointed lumber or cross-laminated timber (CLT). A few favourable properties include a reduced press time, 100 % solid content, invisible bondlines and a long shelf life. In addition no formaldehyde is used, the adhesives are cold-setting and significantly lower spread rates are needed compared to MUF or PRF adhesives in order to achieve ”stable and reliable” bondlines. Furthermore, 1C PUR bondlines show an increased ductility, a characteristic that differs significantly from aqueous or formaldehyde-based adhesives, which are usually more brittle. A more elastic bondline can reach a higher fracture strength and therefore reduce peak stresses at the wood-adhesive interface , which is preferable in the context of green gluing as strong tensile stresses are created during drying due to the shrinkage of the wood (Källander et al. 2008).

As a so-called "moisture-curing" system, meaning that moisture is used as the second component to react, curing is initiated by the reaction of isocyanate and water, which is taken from both the wood and the surrounding air.

$$R - NCO + H_2O \rightarrow R - NH_2 + CO_2$$

(Zeppenfeld and Grunwald 2005)

As "green gluing" (gluing of unseasoned lumber at a high MC above FSP) became more interesting to the wood industry over the last 20 years, several cold-setting adhesive systems were developed and examined, mostly for finger jointing purposes. Besides other adhesive systems such as Greenweld, SoyBond or epoxy adhesives, 1C PUR adhesives were evaluated as suitable for green gluing (Källander et al. 2008). The fact that the hardening chemistry of moisture-curing 1C PUR adhesives is well-suited for bonding wet wood provides additional advantages. Studies done by Sterley (2004, 2012) exhibited deeper penetration into green wood compared to dry wood, performing superior over PRF systems, while the rapid increase in molecular size during the curing process prevents a "starved" glueline, as would happen with conventional adhesives due to excessive absorption. Moreover, no mixing at the processing stage is necessary since mainly the moisture of the wet wood is used as the second component to react with.

The specific 1C PUR adhesive used in this study was manufactured by "PURBOND" (now "Loctite"), Henkel. It needs to be mentioned that although quality assurance testing on wet wood was done successfully by the manufacturer (pers. comm. Ferreira-Netto, Henkel SA, May 2015), a maximum wood moisture content between 16 and 18% is stated in the technical data sheet. Therefore this type of adhesive was not particularly formulated or recommended for green gluing applications. However, a preliminary study for this investigation conducted by the author (see chapter 2) exhibited that good bonding strength results were achieved for varying densities and moisture contents of green edge-glued *Eucalyptus grandis* wood, showing even better results for an increased MC of about 60%.

## 2.3 Defects in wood

According to Panshin et al. (1964, p.251), a defect is described as "any irregularity or deviation from the qualities that make wood suitable for a particular purpose". Some defects develop as natural phenomena in the wood of growing trees and are owed to the environment, whereas others are caused by any subsequent processing of the wood after the trees are felled. In order to minimise wood defects it is crucial to know their origin and to understand their development behaviour. Thus, this section is dedicated to the two main sources of wood defects – growth and drying.

### 2.3.1 Growth-induced wood defects

A tree grows as layers of new cells are added on the outside of the already existing wood tissue. These new wood cells are created by the cambium, a layer of living cells, which is located between the outermost layer of sapwood and the bark (Time 1998). Since the cells tend to shrink in length during the final period of their development, the subsequently added layer of cells is laid down in tension, compressing the adjacent interior tissue. According to Dinwoodie (2000), two theories exist in regard to the longitudinal shrinkage of the developing wood cells. First, the deposition of lignin in the cavities of the cell walls results in lateral swelling and longitudinal contraction, and second, the crystallisation of cellulose causes a natural contraction of the microfibrils in the S2 layer of the cell walls.

As a consequence, longitudinal growth stresses, which are indispensable for a tree in order to maintain its erected position, are developed in the form of tension on the periphery as well as in the form of compression at the centre of a tree (see figure 1) (Panshin et al. 1964). Whereas the amount of tensile stress near the cambium remains almost constant for a wide diameter range, the counterbalancing compression forces, which are developed in the vicinity of the pith, increase with increasing diameter as well as due to a more rapid growth of the tree (Walker et al. 1993).

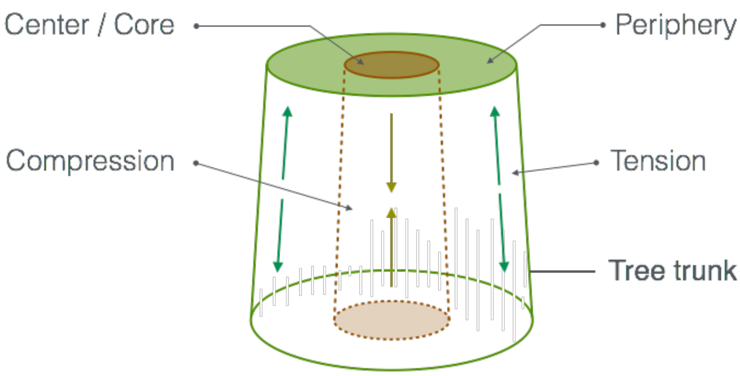


*Figure 1: Internal longitudinal growth stresses in the form of compression in the core and tension on the periphery of the trunk of a tree.*

Whereas in the case of diffuse-porous hardwoods, such as *Eucalyptus grandis*, an increased growth rate only has little impact on the density and associated properties of the timber (e.g. strength and stiffness or magnitude of shrinkage), it can however lead to an increased proportion of corewood compared to trees of slower growth (Walker et al. 1993, Dinwoodie 2000). The wood at the core of a stem is also known as "juvenile wood". This area is known for its low basic density (due to thin cell walls and a lack of latewood formation) and thus decreased strength properties. Furthermore, it has shown an increased tendency for spiral grain and the usually large microfibril angle in the S2 layer of about 30 to 50 degrees causes high longitudinal shrinkage (Walker et al. 1993).

According to Shmulsky and Jones (2011), spiral grain is genetically controlled and can be described by the deviation of the fibre direction from the stem axis, therefore being arranged spirally around it instead of running parallel to it. Common consequences are twist and decreased strength and stiffness properties. Hardwood trees are also known to develop so-called "interlocked grain", which means that the direction of the spiral grain reverses after several years of growing to the opposite direction and thus causes increased longitudinal shrinkage and unpredictable warp. However, it needs to be mentioned that spiralled grain alone has only little effect on wet material since deformation of the sawn timber is created by drying it below fibre saturation point (FSP), due to the unequal shrinkage between the radial and the tangential direction of the wood (Säll 2002) (see section 2.3.2).

Another unfavourable property in this area of the tree is a defect called "brittle heart". It occurs when the longitudinal compression stresses created in the centre of a tree exceed the wood's natural compression strength. As a consequence, the cell walls start to shear and thus the wood in this area becomes considerably weaker (Dinwoodie 2000).

Brittle heart is more likely to be developed in bigger logs, since the corewood compression stresses only increase with increasing diameter. On the other hand a bigger diameter naturally decreases the stress gradient between the pith and the cambium of a tree, as the distance between the two increases, but the magnitude of longitudinal growth stresses on the periphery almost remains equal.

Consequently, as growth stresses are released during the felling of the trees and further processing into lumber, the sawn material from younger trees is more prone for distortion and warping, due to the steeper stress gradient within the stem. Older trees on the other hand, as a result of their larger diameter and hence increased compressive stresses, are more likely to develop heart checks and end-splits (Walker et al. 1993).

According to Walker et al. (1993) and Cassens and Serrano (2004), growth-related warp can become evident in sawn timber in the form of bow, spring and twist (see section 3.2.5 for detailed explanation). It is however not exclusively owed to growth stresses but usually resulting from the interaction with different wood and growth characteristics. Whereas bow is caused by longitudinal growth stresses, twist is the result of spiral grain. In the case of spring it is believed that this type of deformation appears if one of the two narrow edges of a board consists of juvenile or reaction wood and thus showing increased longitudinal shrinkage.

So-called “reaction wood” exists in the form of tension wood in hardwoods and compression wood in softwoods. This very dense tissue is developed in crooked or leaning stems as well as in branches in order to support their upright position. In the case of hardwoods, a highly cellulosic layer (gelatinous layer) is formed in the fibres instead of a usual secondary wall. Thus reaction wood shows excessive shrinkage in the longitudinal direction and, when present together with normal wood within a board, can as well lead to severe warping (Wiedenhoeft 2010, Glass and Zelinka 2010).

### 2.3.2 Drying-induced wood defects

After a tree is felled the green wood begins to dry, which means it loses moisture. This is owed to the hygroscopicity of the wood substance and happens when exposed to an environment with less relative vapor pressure than within the wood itself as it strives to reach a state of balance with the surrounding medium, also known as “equilibrium moisture content” (EMC) (Panshin et al. 1964, Wagenführ and Scholz 2012).

Depending on the species and wood density, freshly sawn, unseasoned timber can have a very high moisture content (MC) of over 200% in the sapwood material (Källander et al. 2008) and therefore needs to be dried down to a MC close to end-use conditions in order to minimize dimensional changes and accompanying defects once the wood is in service. Other reasons for wood drying are for instance the reduction in weight (i.e. easier handling and reduced shipping costs), improved strength and thermal insulation properties, resistance to fungal attack as well as a more effective application of varnish and decay-preventing or fire-retardant treatments (Bergman 2010). Lumber drying can either be conducted in the open air or in a kiln for a more controlled drying process. As various parameters such as relative humidity, temperature and air-flow can be adjusted during the whole duration of drying, customized kiln-schedules were developed in order to meet the needs of different wood species and to keep the amount of drying degradation to a minimum. Whereas softwoods can be kiln-dried from green to dry state (below 12% MC) within four to seven days, hardwood timbers generally require a more gentle treatment and thus the drying process usually takes between about two and three weeks, depending on the wood species (Dinwoodie 2000, Wagenführ and Scholz 2012).

The kiln drying process is initiated by decreasing the relative humidity of the surrounding environment of the wood. Thereby the capillary flow of the free water, which resides in the cell lumina of green wood above fiber saturation point (FSP), is increased and thus the moisture begins to leave the wood structure. Once the MC of the wood is below FSP, which lies at about 27 to 30% MC, all available water is bound in the wood cell walls. Since during the early stage of drying the MC at the surface zone becomes less (already below FSP) but the interior stays wet (still above FSP), the thus created moisture gradient between core and surface consequently stimulates the diffusion of the bound water. Since the water below FSP is chemically bound to the matrix components of the wood cell wall, its evaporation results in the shrinkage of the wood structure and hence in reduced size and weight of the material. Besides relative humidity, the temperature inside the kiln plays an important part and is commonly strongly increased during the progress of drying in order to accelerate the removal of water from the wood (Panshin et al. 1964, Glass and Zelinka 2010).

According to Bergman (2010), the above described moisture gradient between the interior (core) and the outer part (shell) (see figure 2) is the cause of the development of so-called "drying stresses". These stresses are created in the early stages of drying as the drier shell of a piece of wood starts to shrink but the wetter core maintains its size and hence hinders the full shrinkage of the shell. Consequently, tension is created in the shell, together with compression in the wet core. In the case of too rapid drying, the shell gets overstretched and sets in this condition without further shrinkage in the proceeding drying process. When subsequently the core of the wood begins to dry, its shrinkage is prevented by the permanently expanded shell and thus the stresses become reversed as now the core is in tension and the shell goes into compression.

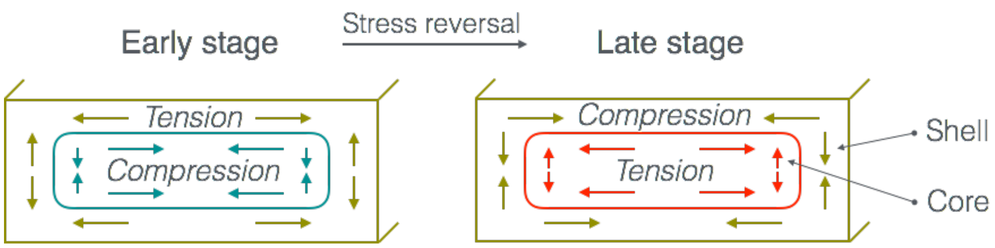


*Figure 2: The development and reverse of stresses in the shell and the core of a piece of lumber during the whole drying period. Adapted from Wagenführ and Scholz (2012).*

The drying stresses, which are developed at the early stage, when the shell is in tension and gets overstretched, can lead to the degradation of the wood material in the form of surface fractures, such as checks (especially on the face of flat-sawn boards) and end-splits (Bergman 2010). According to Crafford (2013), checks are more pronounced in young sawn *Eucalyptus grandis* boards, which contain a relatively large proportion of pith material as compared to lumber from older, bigger diameter trees. End-splits on the other hand are created due to the rapid movement of moisture in the longitudinal direction, which causes the ends of a board to dry very fast. This problem may however be prevented by the application of coatings on the end-grain of the green lumber (Bergman 2010). The early stages of drying are therefore critical, as the manufacturer has to compromise between a short and economical approach and a less severe kiln schedule that keeps the degradation of the lumber quality due to drying stresses to a minimum (Northway 2002).

Further drying-induced defects are honeycombing (internal checks caused by strong tension forces in the core of a board due to a too high kiln temperature in the later stages of drying), cell collapse (crushing or distortion of wood cells due to high stresses caused by shrinkage, usually becoming evident in the form of corrugations) and warp. Besides growth stresses and certain growth characteristics such as distorted grain, varying density, knots or juvenile and reaction wood, most forms of warp are either caused or at least aggravated by the inequality in dimensional change of shrinking wood (Bergman 2010, Sterley 2012). Since wood is an anisotropic material, its change in dimension differs for the three main anatomical directions, namely longitudinal, radial and tangential.

In the longitudinal direction shrinkage is negligible. This is owed to first, the vertical arrangement of the cells within a tree and thus the comparably big distance between the fiber cell walls in this direction, and second, the fairly vertical orientation (about 15 degrees) of the microfibrils in the secondary cell wall (S2), which in case of moisture loss do not shrink in length but move closer together (Panshin et al. 1964, Dinwoodie 2000). This is also a reason shrinkage is considerably more pronounced in both the radial and the tangential direction. Different proposed (but not yet proved) theories regarding the higher level of shrinkage in the tangential compared to radial direction exist to date. First, the presence of shrinkage-restraining wood rays in the radial direction, second, the different shrinkage behavior between earlywood and latewood, and third, the poorer orientation of microfibrils and increased lignification in radial walls (Time 1998). Since wood shrinks more in the tangential direction than in the radial direction, the sawing pattern as well affects the form and magnitude of shrinkage of lumber boards. This is because flat-sawn boards expose a higher proportion of tangential surfaces as compared to quarter-sawn boards and thus show a higher level of unequal shrinkage (Yasin and Raza 1992). As a consequence, flat-sawn boards which are not cut from the center of a stem but with a greater distance from the pith show an increased amount of cup (see figure 3).

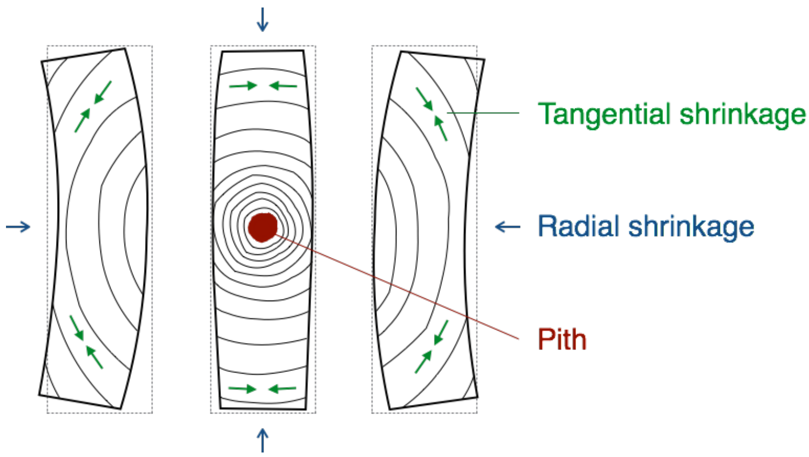


*Figure 3: Development of cup for flat-sawn boards with greater distance from the pith due to unequal shrinkage of the wood between the radial and the tangential direction.*

Another wood characteristic that has an influence on the drying behaviour is the formation of heartwood. Whereas for very young trees the whole stem (from pith to bark) consists of only sapwood, heartwood begins to form with increasing age. It is created from the core of a tree outwards by the deposition of extractives in the cell walls (accumulated by the neighbouring sapwood parenchyma cells) and tyloses clogging the vessels in order to increase durability and resistance to insect and fungal attack. As opposed to sapwood, which is responsible for the water conduction within a living tree, the cells of the often darker, non-conductive heartwood are not metabolically active anymore and thus considered dead. For this reason, the sapwood of a freshly felled tree usually contains considerably more water than the heartwood material (Dinwoodie 2000, Wiedenhoeft 2010, Wagenführ and Scholz 2012). However, according to Bamber (1977) the duration of drying the wood to target MC is almost the same for both materials. This theory implies a significantly faster moisture loss for sapwood owed to the open, unobstructed structure, which consequently often results in an increased amount of checks.

In the case of green gluing, the shrinkage does not merely have an impact on the wood itself, but since the material is already glued together before kiln drying it also affects the bondline with stress, which can consequently lead to damage of the laminated product. Moreover, the elevated temperature during kiln drying can soften the adhesive and thus deform the bondline. It is therefore essential to develop and apply appropriate kiln schedules in order to control this effect (Källander et al. 2008, Sterley 2012).

## 3. Materials and methods

### 3.1 Materials

#### 3.1.1 Timber

Two companies, Biligom International and Merensky Timber, each provided more than 300 green *Eucalyptus grandis* boards for this study. The boards had dimensions of roughly 2400 x 114 x 38 mm (L x W x T) and were divided into two groups of pith-containing boards (P1) and non-pith boards (P0) (see figure 4).

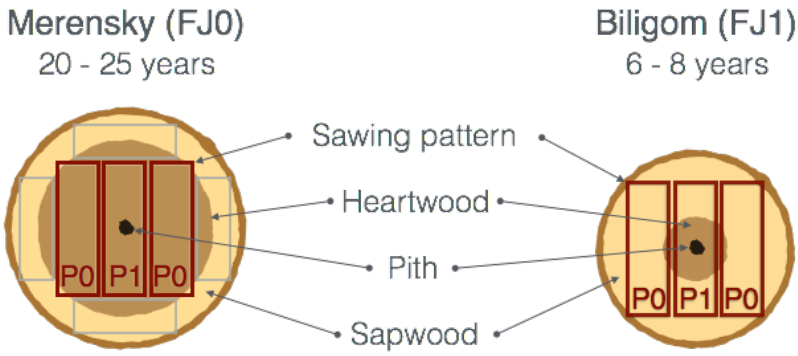


*Figure 4: Applied sawing pattern for flat-sawn Eucalyptus grandis boards from both older Merensky and younger Biligom trees, also showing the position of the pith as well as heartwood and sapwood proportions of the different diameters.*

The material provided by Merensky was between 20 and 25 years of age, whereas the lumber from Biligom was on average six to eight years old (see table 1). After felling, the Biligom logs were left in the plantations for roughly six weeks for initial drying in order to achieve a more equalized moisture distribution throughout the wood for improved subsequent processing and drying of the lumber (pers. comm. Aucamp, Biligom General Manager, April 2016). Furthermore, the Biligom boards were horizontally finger-jointed (fingers visible on the narrow edges of the boards), with each board consisting of between four and five end-jointed pieces of lumber.

All material was obtained from plantations in the Tzaneen area, Limpopo, South Africa. The area has a sub-tropical climate with an average temperature of 15°C in winter and 28°C during the summer months. Rainfall is predominantly found in mid-summer, between November and March, with an average amount of approximately 1230 mm per year. The altitude of the plantations is ranging from 900 up to 2000 m above sea level (pers. comm. Bruwer, Merensky Forestry Manager, March 2016). However, both material sources were cultivated on different plantations and are likely to be of a different genotype.

It has to be noted that the significant differences between the two material sources in terms of genotype, age and pre-treatment (air drying and finger jointing), and hence the varying properties of the wood, make it unsuitable for direct comparison. However, the author had no control over the processing of the wood that was carried out by the supplying companies before the start of the experiment. Furthermore, since the focus of this work was on the potential of green edge gluing to reduce various wood defects, rather than the investigation of the performance of different products, the material selection from two different sources implying varying properties was considered to be reasonable for a comprehensive evaluation.

### 3.1.2 Adhesive

A one-component polyurethane (1C PUR) adhesive, namely "LOCTITE HB S159 PURBOND" (manufactured by Henkel), was employed for this study. According to the manufacturer, the product is formulated on an isocyanate prepolymer basis, with a solids content of 100% and a density of 1160 kg/$m^3$. The particular product "HB S159" has an assembly time of 15 minutes and a curing time of 38 minutes when applied on dry wood between 8 and 18% MC at climate conditions of 20°C and 65% relative humidity. For these standard conditions an adhesive spread rate between 120 and 160 g/$m^2$ is recommended.

It needs to be mentioned that although quality assurance testing on wet wood was done successfully by the manufacturer (pers. comm. Ferreira-Netto, Henkel SA, May 2015), a maximum wood moisture content between 16 and 18% is stated in the technical data sheet. Therefore this type of adhesive was not particularly formulated or recommended for green gluing applications.

## 3.2 Methods

### 3.2.1 Experimental design

In order to investigate how the presence of pith material, age of the timber and finger jointing affect the development of defects, the test boards were divided into four groups according to their characteristics (see table 1). The abbreviations define which groups consisted of younger, finger-jointed material (FJ1) or of older boards without finger-joints (FJ0). The same applies for the presence of pith, with P1 indicating a group of pith-containing boards, whereas P0 groups were exclusively composed of non-pith material.

An additional group was created from Merensky pith material, in order to determine if so-called "stress-relief grooves" (see figure 5) are able to contribute to a reduction of defect development during kiln drying.

**Table 1:** Experimental design consisting of five different material groups distinguished according to their characteristics (age, finger jointing, presence of pith and stress-relief grooves), showing the amount of edge-glued panels produced and control boards selected for each group

| Group name | Abbreviation | Characteristics | Panels | Control boards |
|---|---|---|---|---|
| Billigom, pith | FJ1_P1 | 6 - 8 years old, finger-jointed, including pith | 30 | 30 |
| Biligom, non-pith | FJ1_P0 | 6 - 8 years old, finger-jointed, no pith present | 30 | 30 |
| Merensky, pith | FJ0_P1 | 20 - 25 years old, including pith | 20 | 30 |
| Merensky, non-pith | FJ0_P0 | 20 - 25 years old, no pith present | 30 | 30 |
| Merensky, pith, grooves | FJ0_P1_EG1_G | 20 - 25 years old, including pith and grooves | 10 | - |

30 green edge-glued panels were produced for each of the four different material groups. Ten panels from group FJ0_P1 consisted of boards additionally containing stress-relief grooves (FJ0_P1_EG1_G).

In order to determine if edge gluing of green *Eucalyptus grandis* boards before kiln drying can inhibit the development of defects, a control group, comprising 30 randomly selected non-laminated boards from the same source, was established for each material group. Since the 30 edge-glued groove boards (FJ0_P1_EG1_G) were only compared to their non-grooved equivalents (FJ0_P1_EG1), no control group was established for this group.

All edge-glued material can be recognized by the suffix EG1 throughout this paper, whereas the non-edge-bonded control boards contain EG0 in their abbreviation.

### 3.2.2 Panel production

The edge gluing of green *Eucalyptus grandis* boards was conducted as follows:

1) Since some of the green FJ0_P1 boards showed severe end-splitting due to growth stresses, a pre-selection was carried out for this group in order to exclusively use boards with either no or only slight end-splits. Although this measure violates the assumption of a random sample selection, it provides an improved comparison between the two different lumber sources, as end-splits were already removed from the FJ1 boards as part of the finger jointing process.
2) For each material group, all boards were first processed to equal dimensions, i.e. cut into 2.4 m length and planed to a width of 102 mm in order to obtain a clean surface for edge gluing, which was carried out within the subsequent 24 hours.
3) For group G, two grooves were cut along the longitudinal direction in both wide faces of each board. The grooves were about one third of the board-thickness deep and had a distance of approximately one third of the board-width from the edges on the one face and about a quarter of the board-width from the edges on the other face (see figure 5).

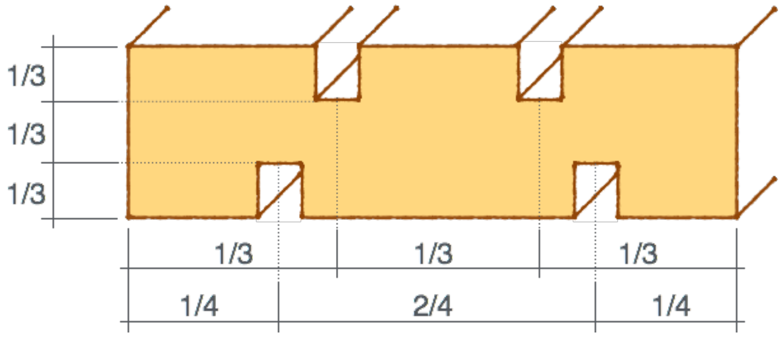


*Figure 5: Illustration of cross-section of board from material group G, showing approximate position and depth of stress-relief grooves.*

4) Five boards were randomly selected for each panel. Each board was checked for abnormalities and defects, which were not part of the investigation of this study. Therefore boards showing severe spring, wane, machine damage or machine skip were not considered (see SANS 1707-1 2010 for definitions of these defects). Boards showing bow were arranged alternately within the panel with respect to their bow direction in order to even out each other when glued together (see figure 6).

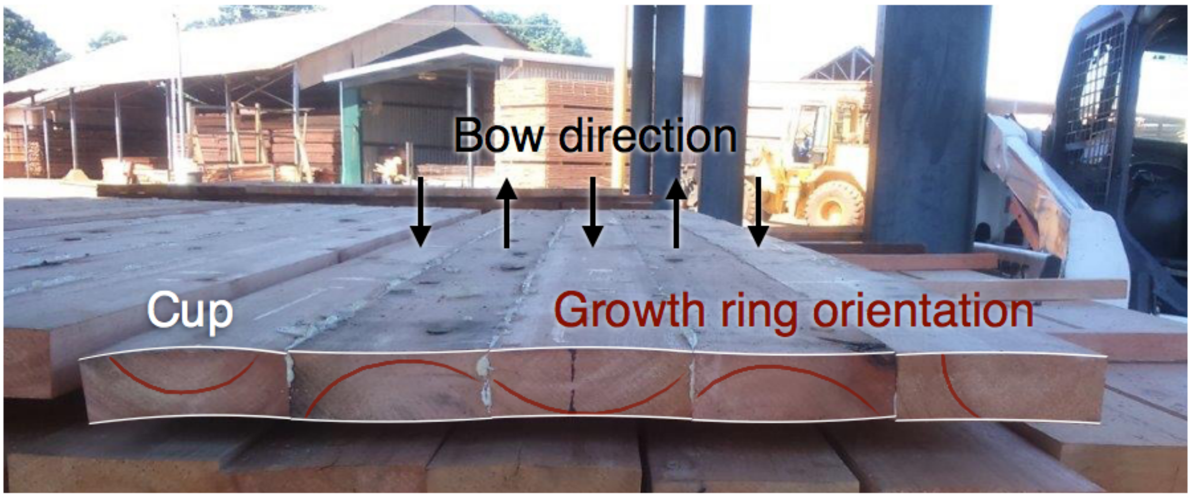


*Figure 6: Photograph of kiln-dried, edge-glued panel, showing alternate layout of boards with respect to bow. Both bow and cup are related to the growth ring orientation. Take note that bow was already present in wet boards whereas cup only manifested after kiln drying.*

5) For every five boards selected for edge gluing, one additional board was randomly selected for the control group. These boards remained unbonded for the purpose of comparison to the edge-glued boards in terms of defect development. Splits and checks of every control board were marked in order to determine the increase in length during kiln drying.
6) The adhesive was applied on four board-edges at a time with a manually operated glue applicator ("OEST Ecopur HK" with "Facetac HAV10", see figure 7) at a spread rate of approximately 180 g/m$^2$.

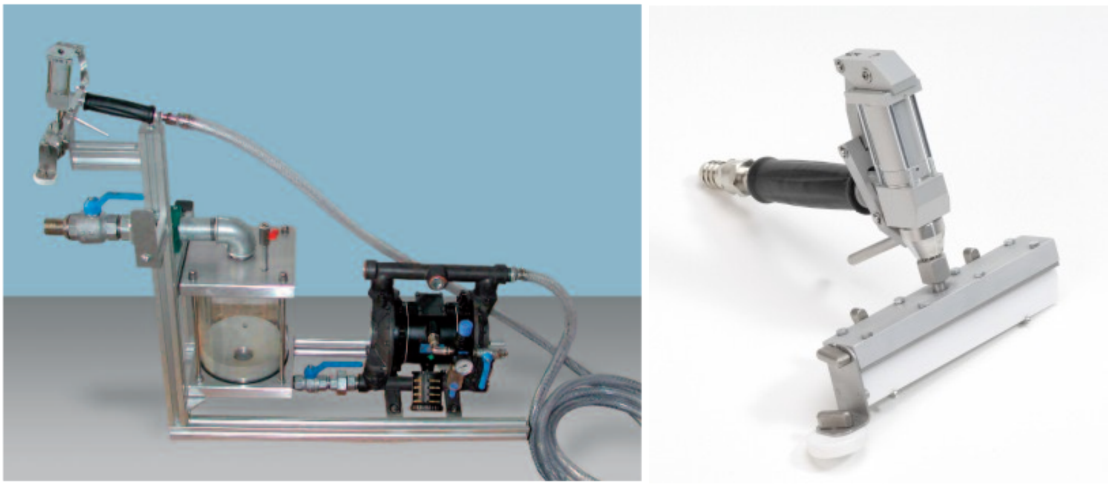

*Figure 7: OEST Ecopur HK dosing system for 1C PUR adhesives (left) and 160 mm wide Facetac HAV10 hand application valve (right) (Oest 2016).*

7) Immediately after gluing, the boards were clamped together in the custom-made rotating edge gluing press shown in figure 8, applying a total pressure of roughly 0.75 MPa. The clamping system was designed and built specifically for this project which allowed fairly rapid manual assembly of panels for the fast setting times of 1C PUR adhesives. In order to straighten the boards during the initial stage of clamping, additional vertical pneumatic clamps forced the boards down on the crosspieces of the press for about 10 to 15 minutes until the next boards were ready for gluing and the panel had to be rotated. Each panel was labelled with the name of the material group in combination with a unique panel number.

*Figure 8: Photograph of the custom-made rotating edge-lamination press in operation.*

8) While under pressure, each panel was allowed to cure for at least 45 minutes before it was released.
9) Each board within a panel was subsequently examined in terms of checks and splits and accordingly marked in order to investigate the extent to which these two defects increased during kiln drying.
10) The panels were stored in stacks under dry conditions for three days before being kiln-dried to a target MC of below 12%.

The whole production, as well as the kiln drying of the material, was carried out at the Merensky hardwood sawmill in Tzaneen, Limpopo, South Africa. The subsequent assessment of defects and determination of material properties (moisture content and basic density) in the dry state took place at the Department for Forest and Wood Science at the University of Stellenbosch, South Africa.

### 3.2.3 Green moisture content

For every three panels produced, one board was randomly selected from the lumber stack for MC determination. In order to obtain a more representative value for the overall MC of a board, two approximately 50 mm wide pieces were cut out at a distance of about one third of the total board length from either end. The green MC of both samples was determined according to SANS 1783-1 (2004) and the calculated average value was used as the final result. Subsequently, the average green MC was calculated for each of the four material groups (see table 2).

### 3.2.4 Kiln drying

To ensure equal drying conditions for all material, the panels, as well as the control boards, were placed in the centre of various kiln-stacks. Hence the material was weighted from above by other wet lumber in order to help inhibit deformation.

The drying of the material was carried out by six-zone progressive kilns manufactured by TF Design, Stellenbosch. A medium temperature drying schedule was applied that allowed the wet *Eucalyptus grandis* lumber to dry below 12% MC in a duration of 24 days.

### 3.2.5 Grading of lumber defects

After drying was completed, the material was again stored under dry conditions for about four weeks before it was transported to Stellenbosch University, South Africa, for grading. Six out of 30 produced panels were randomly selected for each material group in order to compare 30 edge-glued boards to 30 non-laminated control boards. Since the 30 edge-glued groove boards (FJ0_P1_EG1_G) were only compared to their non-grooved equivalents (FJ0_P1_EG1), no control group was established for this group (see table 1). Thus, a total of 270 boards were graded, consisting of 150 edge-glued and 120 control boards. All grading was done according to the SANS 1707-1 (2010) document for structural sawn eucalyptus timber.

1) Check

"*Separation of the wood fibres along the grain of the wood that forms a crack or fissure but does not extend through a piece from one face to the opposite face*" (SANS 1707-1 2010, p.4).

For each of the 270 sample boards, the check lengths of both sides of the board were measured to the nearest 10 mm before and after kiln drying. Subsequently the recorded values were summed up to a total length per side. Up to half the board-length (max. 1.2 m) check length was considered permissible. Below a width of 0.5 mm the fracture was regarded as a hair-check and not taken into account, whereas if the check width exceeded 2 mm, the whole board was rejected. The edge-glued boards were measured twice, first, when still bonded together in the form of panels, and second, after the panels were sawn apart into single boards in order to determine if the separation of the boards caused a change in quantity or dimension of the checks.

2) Split

"*Separation of the wood fibres along the grain of the wood that forms a crack or fissure that extends through a piece from one face to the opposite face*" (SANS 1707-1 2010, p.7).

The split lengths of the sample boards were measured to the nearest of 10 mm before and after kiln drying, with a maximum individual length of 150 mm and a maximum quantity of two splits per board (either one split at each end or two splits at one end) to be permissible. The edge-glued boards were measured twice, first, when still bonded together in the form of panels, and second, after the panels were sawn apart into single boards, in order to determine if the separation of the boards caused a change in quantity or dimension of the splits.

3) Warp

*"Any departure (in the form of bow, cup, spring or twist, or any combination of these) of a true or plane surface of a piece"* (SANS 1707-1 2010, p. 8)

It has to be noted that spring was not considered as a defect criteria within the scope of this study. This is because severe spring might have required an increased pressure at the clamping stage, which would have jeopardised the original purpose of the investigation to assess certain qualities of green edge-glued *Eucalyptus grandis* panels produced under consistent conditions. Also as in the wider perspective the recovery rate of the edge-glued panels will become important, spring, as opposed to bow, cup and twist, may likely not be of great interest as the boards get straightened when clamped and glued together.

In order to ensure the accurate measurement of warp in the form of bow and twist, the custom-made device shown in figure 9 was employed. The device has three equally long pins (A, B, C), which create an even plane for the board to rest on. On one end of the board a weight is placed on top, which forces it onto pin A and B, whereas the self-weight of the board keeps it lying on pin C. Thus the deviation of the board from the even level can be measured at the measuring points 1 and 2 for bow and at measuring point 3 for twist.

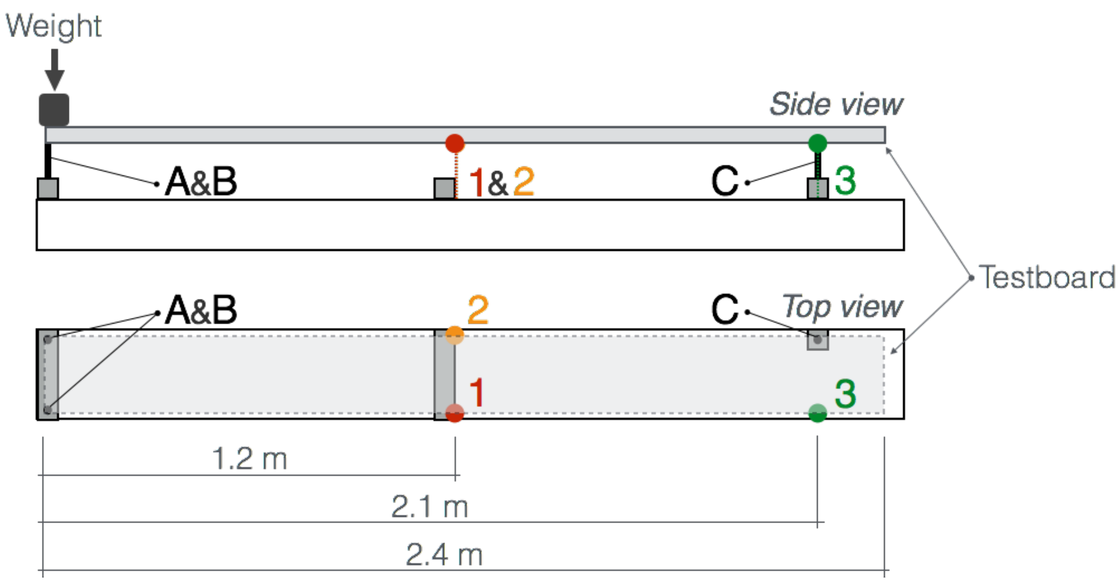


*Figure 9: Side elevation and top view of the measuring device used for the determination of bow and twist, showing dimensions as well as pins (A, B, C) and measuring points (1, 2, 3).*

3.1) Bow

"*Lengthwise curvature, in its own plane, of an edge of a piece*" (SANS 1707-1 2010, p.4).

Bow was measured at half the board length (1.2 m from each end) on both sides of board's width (measuring points 1 and 2, see figure 9) to the nearest 1 mm. The average between the two measured values was calculated to determine the final result.

3.2) Twist

"*Form of warp that appears as lengthwise spiral distortion in a piece*" (SANS 1707-1 2010, p.8).

Twist was measured at a board length of 2.1 m (measuring point 3, see figure 9). This was done since not all boards were exactly 2.4 m long but some of them were slightly shorter. According to the SANS 1707-1 (2010) document, the next shorter length to use for twist determination is 2.1 m, having the same permissible maximum value of 5 degrees as for a board length of 2.4 m.

3.3) Cup

"*Curvature that occurs in the transverse section of a piece of timber*" (SANS 1707-1 2010, p.4).

Cup was measured at the worst position of both ends of each board to the nearest 1 mm. The highest measured value was used as the final result.

### 3.2.6 Basic density and air-dry moisture content

In order to determine the basic density of the boards as well as their air-dry MC, one approximately 5 mm wide sample was cut out of each board at a distance of roughly one third of the board length from one of the board's ends. Since the finger-jointed boards (FJ1) consisted of usually four to five end-jointed lumber pieces with assumingly slightly varying properties, an additional sample was taken from these boards at another position in order to obtain more accurate results. All samples comprised the whole cross section and were free from knots and other defects.

The MC of the air-dry samples was determined according to SANS 1783-1 (2004) and the basic density according to the maximum moisture content method for the determination of specific gravity of small wood samples (Smith 1954). For the latter one, the samples were placed underwater in a vertical pressure vessel and weighted in order to stay submerged, while several pressure/vacuum cycles between -100 kPa (-1 bar) and 700 kPa (7 bar) were carried out until complete saturation of the wood was reached.

### 3.2.7 Statistical analysis

The Statistica 13 software was employed to verify that the obtained data fulfilled the assumptions of normal distribution and homogeneity of variance before performing a factorial design analysis of variance (ANOVA) on the test results in order to determine the influence of the age and finger-jointing of the timber, presence of pith material and edge gluing on the development of the various investigated defects. Furthermore, t-tests were conducted to determine the effect of stress-relief grooves on defect development, comparing the groove-cut material (FJ0_P1_EG1_G) to its non-grooved equivalent group (FJ0_P1_EG1). Since both defects, check and split were measured before and after kiln drying, the increment during the drying stage was investigated as well.

## 4. Results and discussion

### 4.1 Moisture content and basic density

**Table 2:** Average moisture content before and after kiln drying as well as average basic density of the four different material groups, including t-test p-values for determination of significance of difference

| Material group | Green MC [%] | Air-dry MC [%] | Basic density [kg/m$^3$] |
|---|---|---|---|
| **FJ1_P1** | 87.8 | 9.5 | 381.2 |
| **FJ1_P0** | 78.2 | 9.5 | 380.7 |
| **FJ0_P1** | 65.3 | 9.5 | 431.1 |
| **FJ0_P0** | 62.9 | 9.7 | 433.5 |
| **T-test p-values** | **Green MC** | **Air-dry MC** | **Basic density** |
| **FJ1_P1 vs. FJ1_P0** | 0.22 | 0.82 | 0.78 |
| **FJ0_P1 vs. FJ0_P0** | 0.38 | 0.02* | 0.53 |
| **FJ1 vs. FJ0** | <0.01* | 0.71 | <0.01* |

** These groups were statistically significant from each other at a 5% significance level.*

Table 2 shows the results for the average green MC, air-dry MC and basic density of the four material groups as well as the t-test p-values, which were used to determine if the means of two groups were statistically different at a 5% significance level.

The FJ1_P1 material had an average green MC of roughly 88% and the FJ1_P0 boards of about 78%. However, with a p-value of 0.22, the null hypothesis that the means of both groups are equal could not be rejected and thus the difference in green MC was considered to be due solely to natural variation. Due to the equal average density of 381 kg/m$^3$ and a high p-value of 0.78, similar material properties can be assumed for both groups (FJ1_P1 and FJ1_P0), which concludes that either no or only little heartwood was developed by the young trees at the age of six to eight years (see figure 4). This would as well correspond to the results of Palermo et al. (2015), where a transition age from juvenile to mature wood in *Eucalyptus grandis* trees is stated between eight and 13 years of age.

For the FJ0 material, both groups (FJ0_P1 and FJ0_P0) showed a similar green MC of about 63 to 65% with a p-value of 0.38. These results coincide with the values obtained for green *Eucalyptus grandis* boards in the second chapter of this study, which consisted of solely heartwood material and had a green MC of approximately 55 to 63% (Pröller 2017). Taking also into account the almost equal average basic density of the two groups (FJ0_P1: 431 kg/m$^3$ and FJ0_P0: 434 kg/m$^3$, p-value: 0.53) and the fact that the trees were already between 20 and 25 years of age at the time of felling, it can be assumed that probably all FJ0 boards exclusively consisted out of heartwood (see figure 4).

The results for the air-dry MC between group FJ0_P1 and group FJ0_P0 differed significantly from each other at a 95% confidence level, with a p-value of 0.02. However, due to the small magnitude of the difference (0.2% on average) as well as the probably negligible impact on the grading results, it was not further considered important for the following interpretation of the obtained test results.

Additional t-tests were carried out in order to determine if the green MC as well as the basic density differs between the FJ1 and FJ0 material. It turned out that in both cases a significant difference was obtained with very small p-values of clearly below 0.01. This means that the younger, finger-jointed material (FJ1) showed an increased green MC but decreased basic density compared to the older, not finger-jointed boards (FJ0). The differences in density could be due to genetics, management, environment and probably also the increased presence of extractives in the older material as extractives were not removed before density determination.

### 4.2 Board rejections according to the SANS 1707-1 (2010) grading requirements

**Table 3:** Number and percentage of board rejections due to the various investigated defects according to the SANS 1707-1 (2010) grading requirements

| Non-laminated boards | Percentage [%] | Number of rejected boards | | | | |
|---|---|---|---|---|---|---|
| | | Check | Split | Twist | Cup | Bow |
| **FJ1_P1_EG0*** | 13.3 | 4 | 0 | 1 | 0 | 0 |
| **FJ1_P0_EG0**** | 31.0 | 3 | 2 | 3 | 1 | 0 |
| **FJ0_P1_EG0** | 10.0 | 3 | 0 | 0 | 0 | 0 |
| **FJ0_P0_EG0** | 10.0 | 1 | 2 | 0 | 0 | 0 |
| **Total** | **16.0** | **11** | **4** | **4** | **1** | **0** |

| Edge-glued boards | Percentage [%] | Number of rejected boards | | | | |
|---|---|---|---|---|---|---|
| | | Check | Split | Twist | Cup | Bow |
| **FJ1_P1_EG1** | 26.7 | 4 | 4 | 0 | 0 | 0 |
| **FJ1_P0_EG1** | 20.0 | 6 | 0 | 0 | 0 | 0 |
| **FJ0_P1_EG1*** | 26.7 | 3 | 2 | 3 | 1 | 0 |
| **FJ0_P0_EG1** | 0 | 0 | 0 | 0 | 0 | 0 |
| ***FJ0_P1_EG1_G**** | *20.0* | *4* | *2* | *0* | *0* | *0* |
| **Total** | **18.3** | **13** | **6** | **3** | **1** | **0** |

** One board of this group was rejected due to two different defects. Therefore the number and the percentage of the rejected boards do not correspond with each other.*
*** This group comprised only 29 boards as opposed to the other groups with 30 boards.*
**** This group was not counted into the total sum of rejections, since no non-laminated control group was established to compare it to.*

Table 3 exhibits that a slightly higher percentage of edge-glued boards (EG1) (18.3%) compared to non-laminated boards (EG0) (16%) did not comply with the requirements of the SANS 1707-1 (2010) for sawn eucalyptus structural timber.

In total, check turned out to be the most critical defect, with about 10% of all tested boards exceeding the maximum permissible dimensions. This coincides with the findings of Crafford (2013) where most of the young and finger-jointed *Eucalyptus grandis* boards were rejected due to check (36%). The second-most board rejections were owed to split (4%), followed by twist (3%) and cup (less than 1%). No board exceeded the maximum dimension for bow according to the SANS 1707-1 (2010) document. Overall, the older material (FJ0) showed a smaller rejection rate as compared to the younger, finger-jointed material (FJ1). The lumber from group FJ0_P0 performed best, accounting for only about 7% of the total amount of rejected boards, whereas the highest amount of rejections of approximately 35% was caused by group FJ1_P0.

A few boards of group FJ0_P1_EG_G showed significant damage and deformation due to the groove cuts (see figure 10) and thus could no longer be considered for structural purposes due to visual as well as possible strength-related deficiencies.

*Figure 10: Significant deformation and damage of boards due to the presence of stress-relief grooves.*

### 4.3 Increment of check and split lengths during kiln drying

Each board was investigated regarding check and split both before and after kiln drying in order to determine the increment of these defects during the actual kiln drying process. Table 4 shows the average total length of both defects per board for every material group, including the non-laminated control groups (EG0). Since no change in dimension or quantity of the checks and splits occurred for the boards after they were sawn apart from edge-glued panels into single boards, this comparison does not appear in the table.

**Table 4:** The average total check and split length per board in mm for each material group, both before and after kiln drying, including the increment

| **Group** | **Check length** [mm] | | | **Split length** [mm] | | |
|---|---|---|---|---|---|---|
| | **Before kiln drying** | **After kiln drying** | **Increment** | **Before kiln drying** | **After kiln drying** | **Increment** |
| **FJ1_P1_EG1** | 19.3 | 33.9 | 14.6 | 0.7 | 5.6 | 4.9 |
| **FJ1_P1_EG0** | 13.1 | 29.2 | 16.1 | 0.8 | 1.8 | 1.0 |
| **FJ1_P0_EG1** | 41.4 | 54.1 | 12.7 | 0.0 | 0.7 | 0.7 |
| **FJ1_P0_EG0** | 25.5 | 33.8 | 8.3 | 0.6 | 2.0 | 1.4 |
| **FJ0_P1_EG1** | 16.5 | 29.0 | 12.5 | 3.9 | 4.7 | 0.8 |
| **FJ0_P1_EG0** | 12.4 | 23.5 | 11.1 | 4.3 | 5.8 | 1.5 |
| **FJ0_P0_EG1** | 5.3 | 7.3 | 2.0 | 2.2 | 3.0 | 0.8 |
| **FJ0_P0_EG0** | 3.4 | 7.5 | 4.1 | 6.8 | 7.2 | 0.4 |
| ***FJ0_P1_EG1_G*** | *17.7* | *22.3* | *4.6* | *2.4* | *4.8* | *2.4* |

Table 4 shows that both defects, check and split, increased for all material groups during the kiln drying process. On average, each finger-jointed board (FJ1) had a total check length of 37.8 mm, whereas the FJ0 boards showed significantly lower results with an average value of 16.8 mm. Furthermore, about 60% of the total check length for all boards was already created before kiln drying (63.4% for group FJ1 and 56.9% for group FJ0). Since checks develop at the early stage of drying (Bergman 2010), this was probably owed to preceding air-drying, which happens naturally after a tree is felled and further processed into sawn timber.

In terms of split, the older material (FJ0) exhibited an average total length of 5 mm per board, which was twice as much as compared to the younger FJ1 boards (2.5 mm). The reason for that may have been the increased age of the FJ0 material, which according to Walker et al. (1993) leads to higher compressive stresses in the corewood of a tree and thus increased heart-check and end-split development. Moreover, the cross-sections of the FJ1 boards were sprayed, which probably inhibited the creation of end-splits by slowing down the longitudinal moisture loss (Bergman 2010).

## 4.4 Impact of material properties and green edge gluing on defect development

A factorial design ANOVA was carried out in order to determine how the different material groups and their associated characteristics (age, finger jointing, presence of pith) as well as the edge gluing of green *Eucalyptus grandis* boards before kiln drying influence the development of defects, namely check, split and warp in the form of bow, cup and twist. Since it turned out that in most cases a notable amount of check and split was already created before kiln drying to varying extents between the material groups (see table 4), the investigation was carried out based on the increment of both defects during kiln drying instead of the total end length in order to determine if the edge-bonding of the green boards affected the development of checks or splits.

For each defect the associated ANOVA table is shown in order to display the significance of the various factors as well as their interactions with each other. The significant interactions of highest order were used as centre point of investigation and are presented in the form of a graph.

If the Levene's test (equality of variances) for one of the following interactions was significant at a level of 0.01 (<1%), a more conservative weighted means graph was generated and reported instead of the LS (least-squares) means version.

### 4.4.1 Check increment

**Table 5:** ANOVA table showing the significance of pith presence, green edge gluing, material age and finger jointing for the development of check during kiln drying

| Effect | SS | Degr. of Freedom | MS | F | p |
|---|---|---|---|---|---|
| Intercept | 206.5912 | 1 | 206.5912 | 582.4055 | 0.000000 |
| Pith | 9.8064 | 1 | 9.8064 | 27.6453 | 0.000000 |
| Edge-glued | 0.2268 | 1 | 0.2268 | 0.6393 | 0.424781 |
| Finger-jointed | 9.4011 | 1 | 9.4011 | 26.5029 | 0.000001 |
| Pith*Edge-glued | 0.0821 | 1 | 0.0821 | 0.2314 | 0.630910 |
| Pith*Finger-jointed | 0.3262 | 1 | 0.3262 | 0.9196 | 0.338582 |
| Edge-glued*Finger-jointed | 0.0817 | 1 | 0.0817 | 0.2302 | 0.631825 |
| Pith*Edge-glued*Finger-jointed | 0.4833 | 1 | 0.4833 | 1.3625 | 0.244314 |
| Error | 81.9404 | 231 | 0.3547 | | |

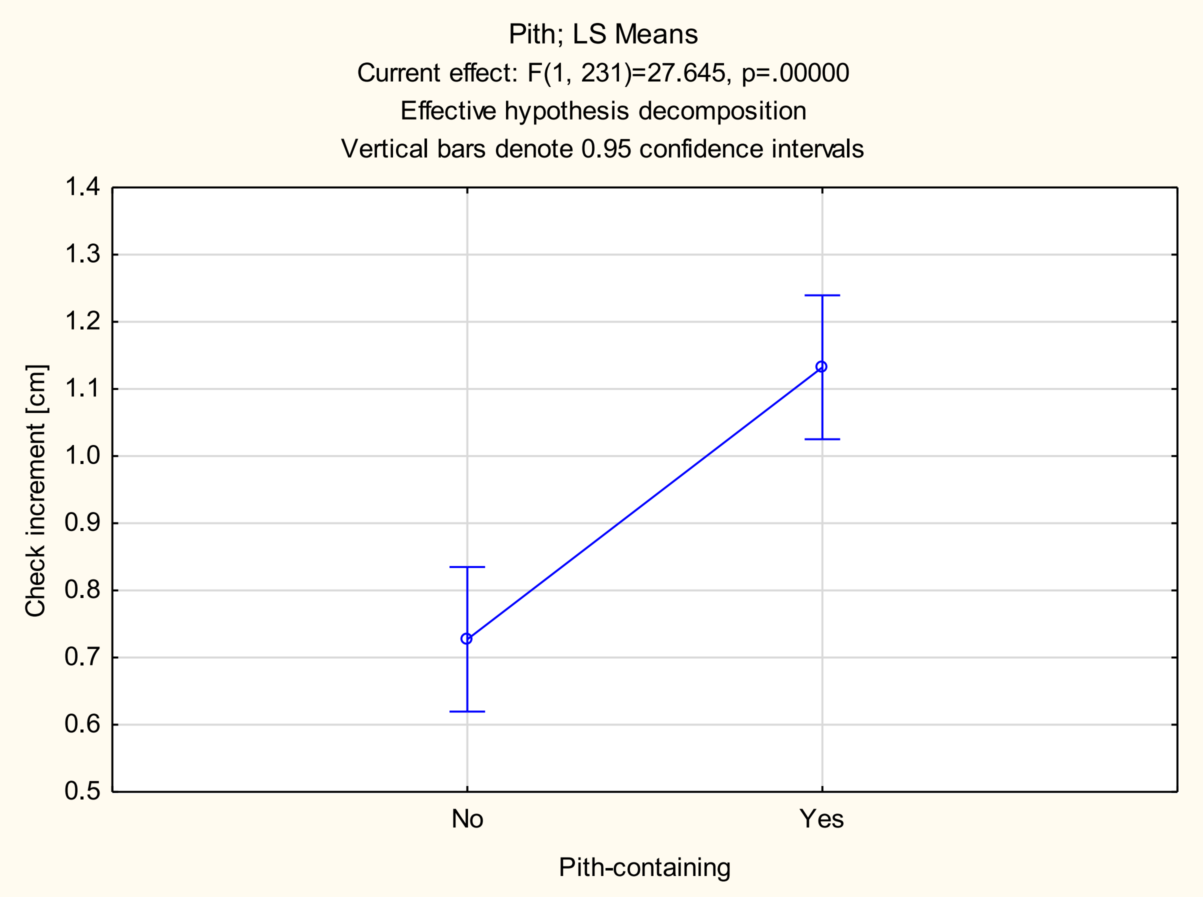


*Figure 11: Graph showing the presence of pith in the material as a significant factor for the increment of check during kiln drying.*

The presence of pith in regard to check development during kiln drying was found to be statistically highly significant, showing a very small p-value below 0.001.

Figure 11 shows that an increased amount of check was developed during kiln drying for pith-containing material (P1) compared to boards without pith (P0). This corresponds with the results obtained by Crafford (2013), which exhibited a significant increase of check for *Eucalyptus grandis* boards with an increased proportion of pith material. The higher tendency to develop checks close to the pith can probably be attributed to the unfavourable properties of the juvenile wood, in particular the combination of compressive stresses, low basic density and increased longitudinal shrinkage, causing the comparably weak corewood tissue to rupture (Walker et al. 1993).

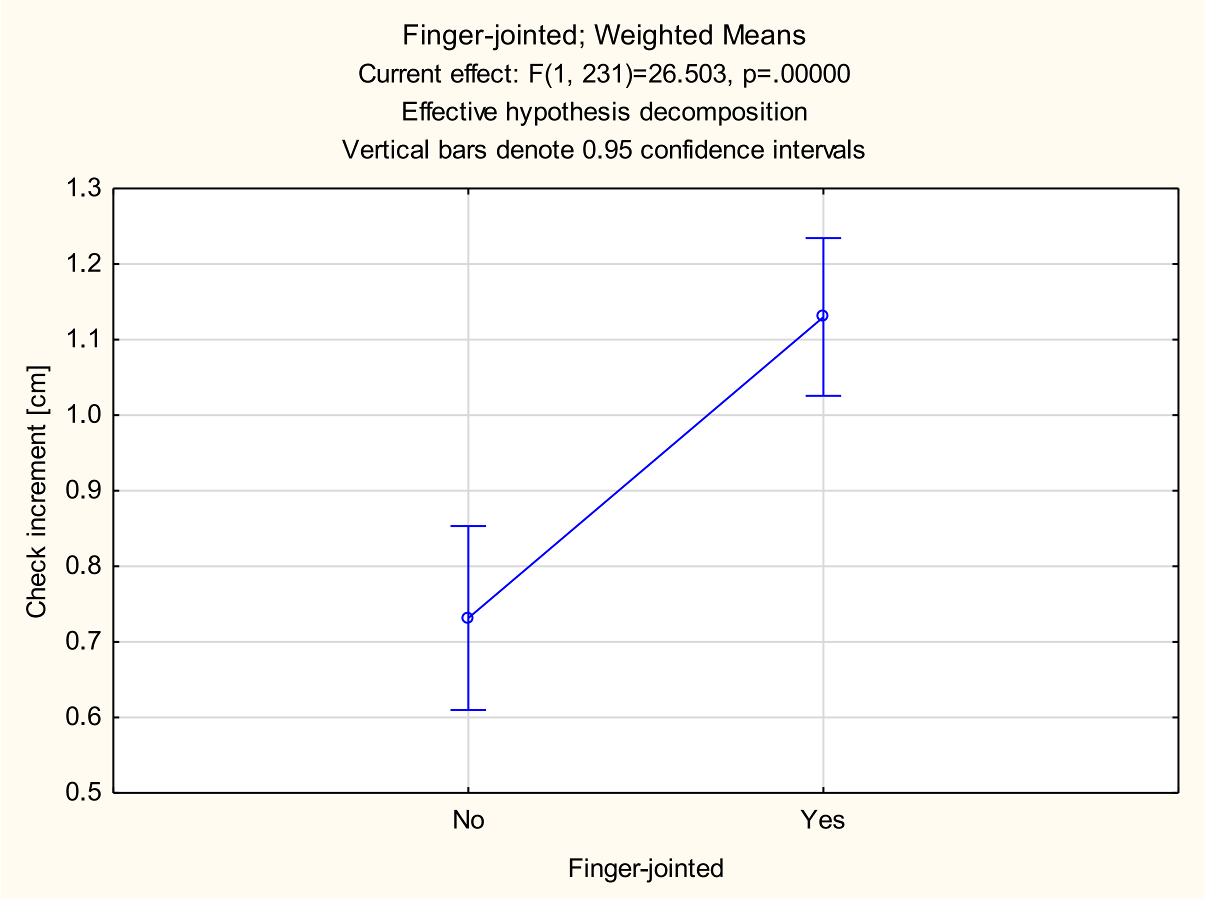


*Figure 12: Graph showing the different lumber sources as a significant factor for the increment of check during kiln drying.*

The two different sources of lumber in regard to check development during kiln drying were also statistically highly significant at a 1% level, showing a p-value below 0.001.

According to figure 12, the younger, finger-jointed material (FJ1) developed more check during the kiln drying stage as compared to the older not finger-jointed boards (FJ0). These results comply with the findings of Crafford (2013), where 5 year old *Eucalyptus grandis* boards exhibited significantly more check than older boards with 11 and 18 years of age, respectively.

This might be explained by the disparate material compositions of the two lumber sources, as it is likely that the older material (FJ0) was in large part composed of heartwood, whereas the younger boards (FJ1) probably consisted of sapwood to a great extent (see figure 4). Since sapwood is able to contain significantly higher amounts of water than heartwood, but both materials season in about the same time, this implies a more rapid initial moisture loss for the younger material (FJ1) (Bamber 1977). In consequence, a larger moisture gradient between the wet core and the drying shell was created for the FJ1 boards, which is known to be the cause for the creation of surface checking (Bergman 2010).

The study conducted by Crafford (2013) showed that check was one of the critical defects which led to the repudiation for the structural utilisation of *Eucalyptus grandis* lumber according to the South African national standard. Since the statistical analysis of the obtained results did not find the edge-lamination of the green boards statistically significant, it must be assumed that green edge gluing is not able to contribute to the reduction of check development in *Eucalyptus grandis* lumber.

### 4.4.2 Split increment

**Table 6:** ANOVA table showing the significance of pith presence, green edge gluing, material age and finger jointing for the development of split during kiln drying

| Effect | SS | Degr. of Freedom | MS | F | p |
|---|---|---|---|---|---|
| Intercept | 5.62802 | 1 | 5.628020 | 50.12427 | 0.000000 |
| Pith | 0.49788 | 1 | 0.497875 | 4.43418 | 0.036306 |
| Edge-glued | 0.01999 | 1 | 0.019993 | 0.17807 | 0.673434 |
| Finger-jointed | 0.05408 | 1 | 0.054079 | 0.48163 | 0.488380 |
| Pith*Edge-glued | 0.13071 | 1 | 0.130710 | 1.16413 | 0.281737 |
| Pith*Finger-jointed | 0.09625 | 1 | 0.096251 | 0.85723 | 0.355481 |
| Edge-glued*Finger-jointed | 0.16982 | 1 | 0.169822 | 1.51247 | 0.220013 |
| Pith*Edge-glued*Finger-jointed | 0.44941 | 1 | 0.449412 | 4.00256 | 0.046602 |
| Error | 25.93699 | 231 | 0.112281 | | |

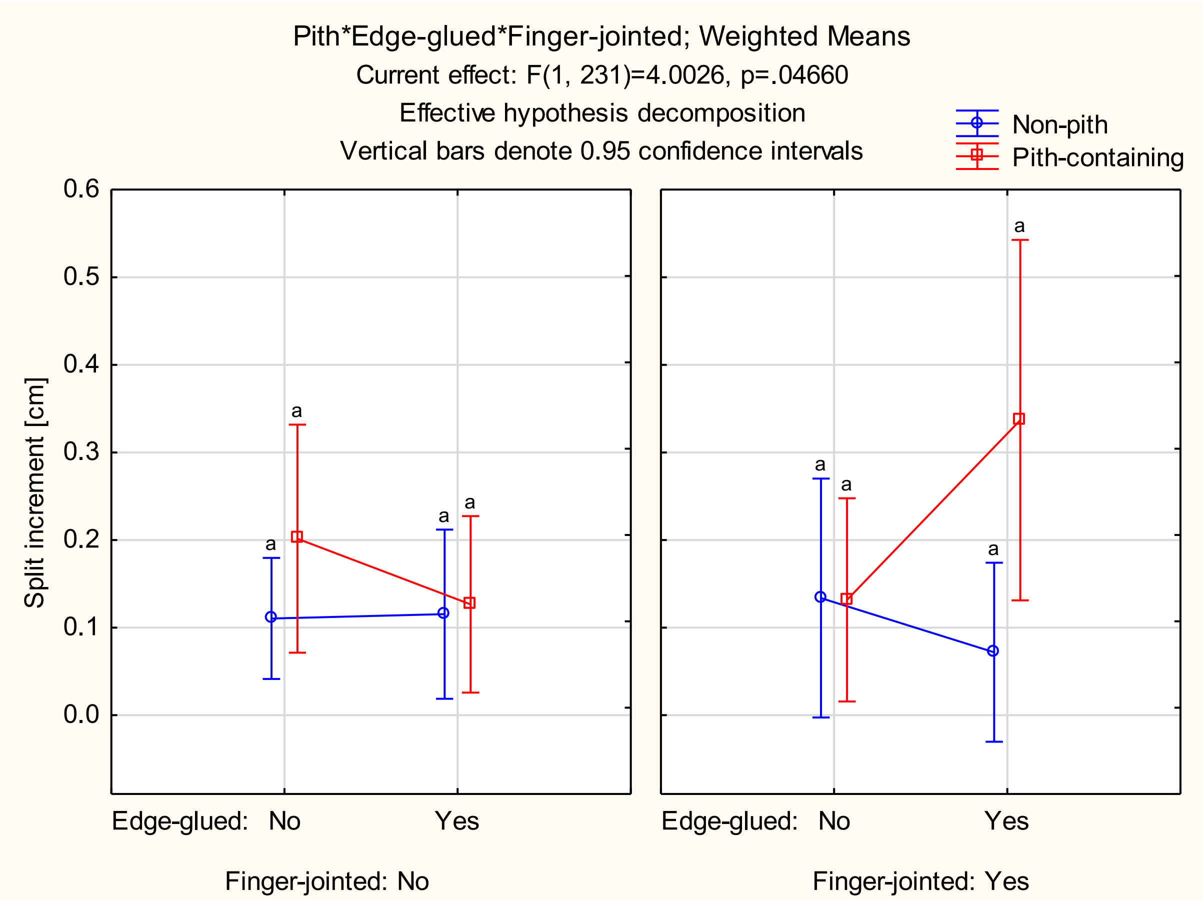


*Figure 13: Significant three-way interaction between the presence of pith, green edge gluing and the two different lumber sources for the increment of split during kiln drying.*

Although the three-way interaction between the presence of pith, green edge gluing and the two different lumber sources was statistically significant for the split increment during kiln drying at a 5% significance level, the p-value was close to 0.05 and the weighted means graph did not show significant differences (see figure 13). For this reason, the three-way interaction is not interpreted in this paper, but instead the presence of pith as a significant factor.

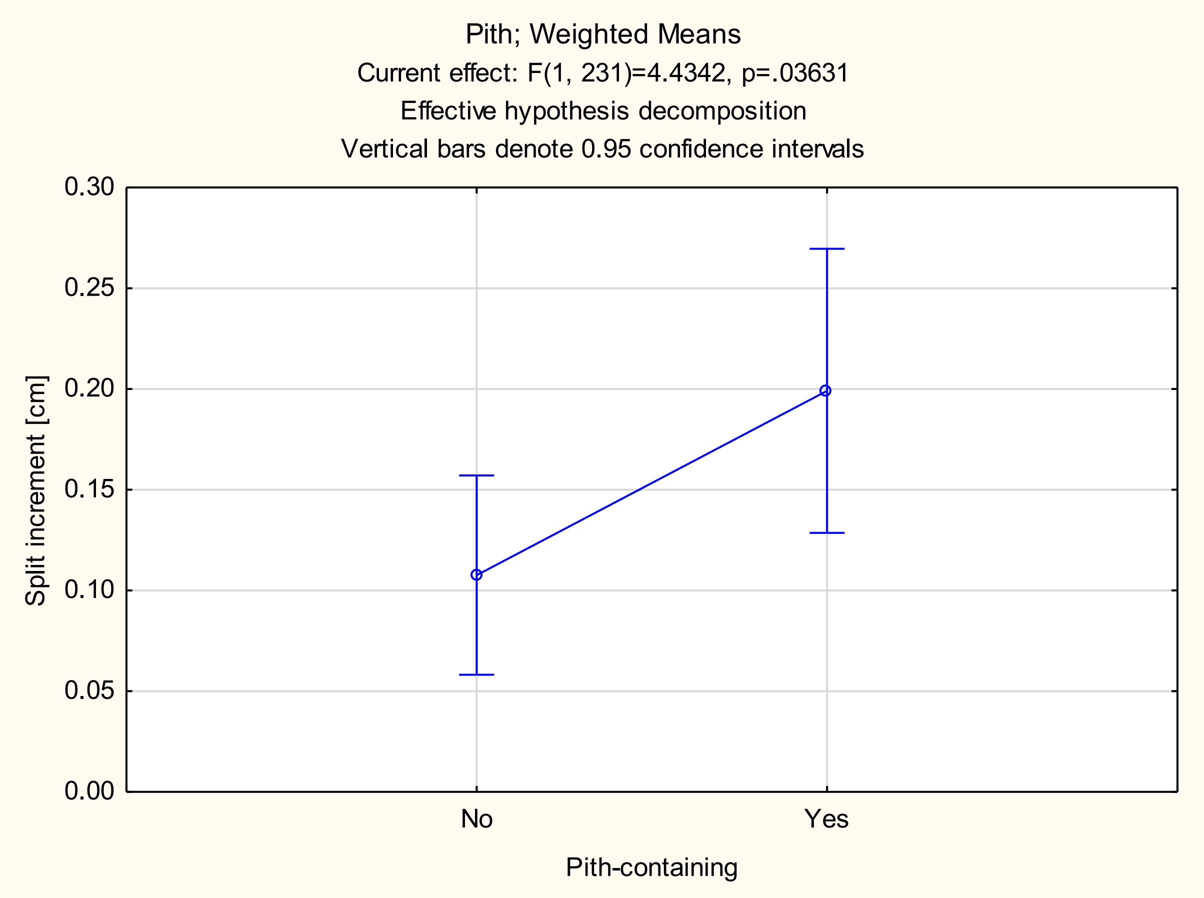


*Figure 14: Graph showing the presence of pith as a significant factor for the development of end-split during kiln drying.*

The presence of pith was found to be statistically significant at a 95% confidence level regarding the development of split during kiln drying with a p-value of 0.036.

Figure 14 shows that an increased increment of split length during kiln drying was obtained for pith-containing boards (P1) as compared to boards with a greater distance from the pith (P0). Since split occurred exclusively in the form of end-splits, this can be explained by the large proportion of juvenile wood in pith-containing boards (P1). Juvenile wood is known for its growth-related longitudinal compressive stresses, which can cause end-splitting as well as heart-checks (Walker et al. 1993).

Since edge gluing of the green *Eucalyptus grandis* boards was not found to be a significant factor for the increment of split during kiln drying, it must be assumed that it could not contribute to the reduction of split development.

### 4.4.3 Bow

**Table 7:** ANOVA table showing the significance of pith presence, green edge gluing, material age and finger jointing for the development of bow

| Effect | SS | Degr. of Freedom | MS | F | p |
|---|---|---|---|---|---|
| Intercept | 4372.758 | 1 | 4372.758 | 700.0179 | 0.000000 |
| Pith | 18.980 | 1 | 18.980 | 3.0385 | 0.082643 |
| Edge-glued | 26.793 | 1 | 26.793 | 4.2892 | 0.039466 |
| Finger-jointed | 1.111 | 1 | 1.111 | 0.1778 | 0.673656 |
| Pith*Edge-glued | 19.960 | 1 | 19.960 | 3.1954 | 0.075159 |
| Pith*Finger-jointed | 34.630 | 1 | 34.630 | 5.5438 | 0.019385 |
| Edge-glued*Finger-jointed | 13.651 | 1 | 13.651 | 2.1854 | 0.140690 |
| Pith*Edge-glued*Finger-jointed | 2.883 | 1 | 2.883 | 0.4616 | 0.497573 |
| Error | 1442.973 | 231 | 6.247 | | |

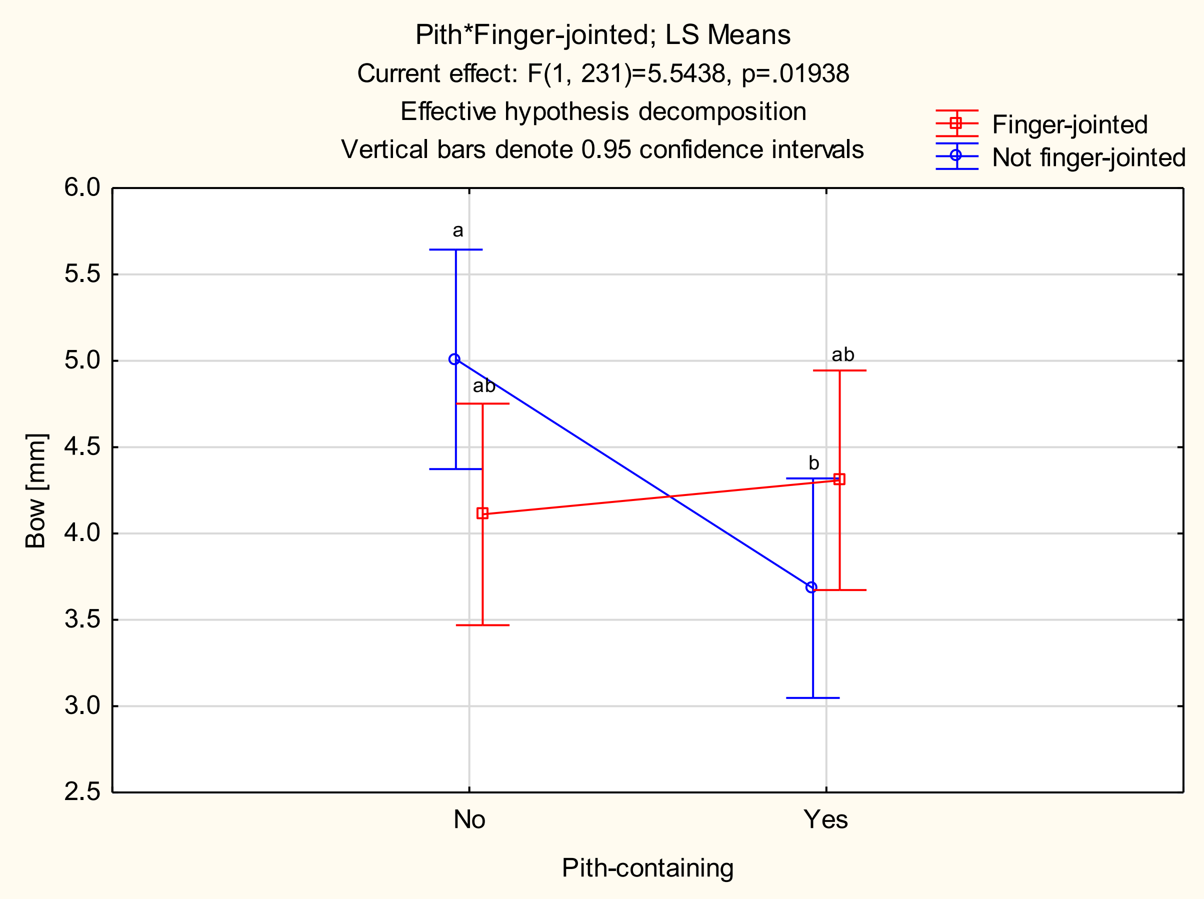


*Figure 15: Significant two-way interaction between the two different lumber sources and the presence of pith for the development of bow.*

With a p-value of 0.019, the two-way interaction between the two different material sources and the presence of pith in regard to bow development was statistically significant at a 95% confidence level.

Figure 15 exhibits that the older material (FJ0) showed increased bow for boards with a greater distance from the pith (P0), whereas no difference between P1 and P0 boards for the younger, finger-jointed material (FJ1) was obtained.

According to Walker et al. (1993) bow is caused by longitudinal growth stresses (figure 1) in flat-sawn boards with a greater distance from the pith (P0) (figure 4). Consequently, the shortening of the lumber along the grain results in an appreciable decrease of lengthwise curvature. Since the finger-jointed boards (FJ1) consisted of usually four to five shorter, end-to-end jointed pieces of lumber, the level of bow stayed fairly constant, regardless of its original position in the tree.

Increased bow for older, not finger-jointed boards (FJ0) was already observed before the boards were edge-glued together. This is because of the longitudinal growth stresses, which exists in both the core (compressive stresses) and the periphery (tensile stresses) of the stem (figure 1) (Walker et al. 1993). Flat-sawn, pith-containing boards (P1) are taken from the centre of the stem, consequently their wide faces are not exposed to unequal stresses, whereas the wide faces of non-pith, flat-sawn boards (P0), which are closer to the periphery (figure 4), are more in tension towards the bark than towards the pith, which consequently causes them to bow.

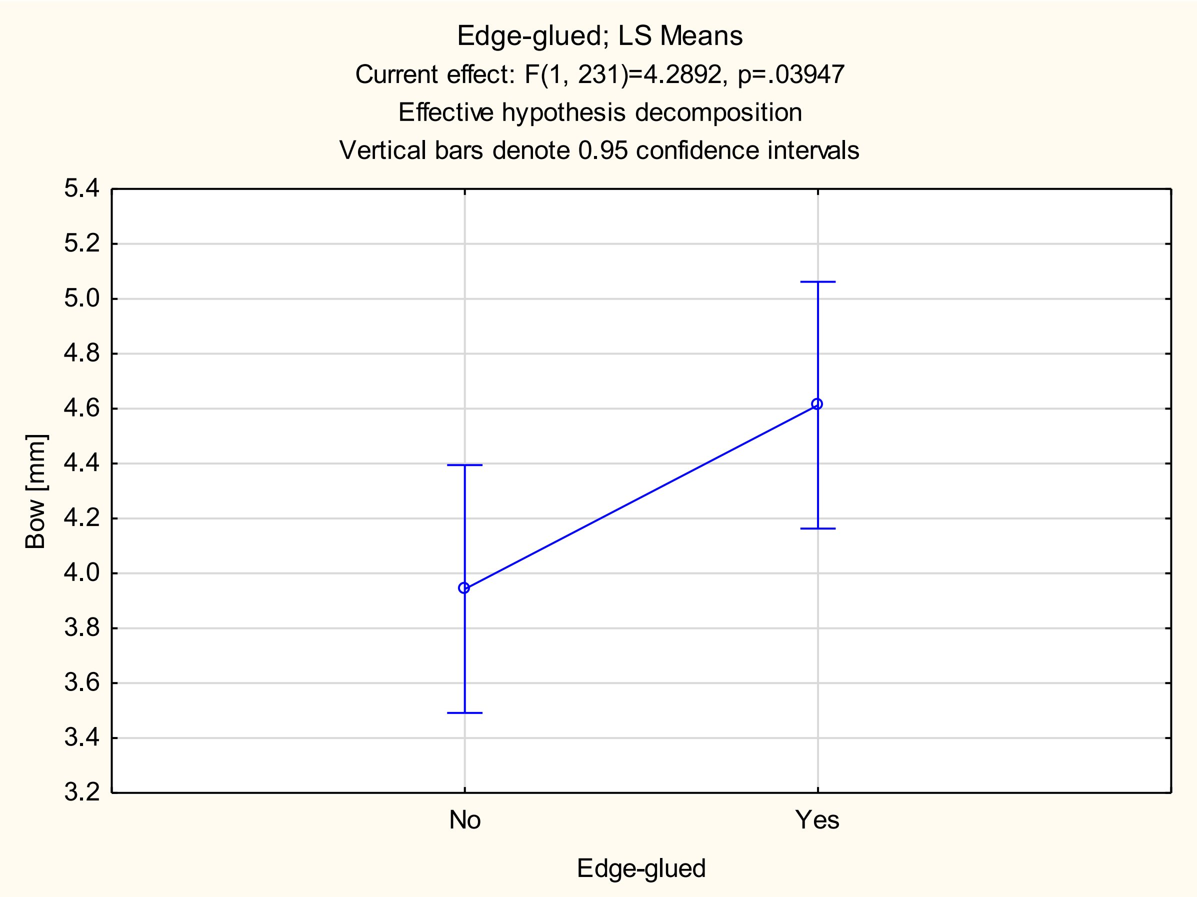


*Figure 16: Graph showing edge gluing as a significant factor for the development of bow.*

Edge gluing was found to be statistically significant in regard to bow development at a 95% confidence level, showing a p-value of 0.039.

According to figure 16, the development of bow increased when the boards were edge-glued before kiln drying. No logical explanation for this behaviour could be found by the author as rather the opposite was expected to result. However, it has to be noted that the magnitude of the average difference between the two groups (EG0 and EG1) was too small to have a practical impact, since a variation of about 0.6 mm on a board length of 2.4 m can be considered negligible.

It was visually observed that the lengthwise deformation of FJ0_P0 boards, which already showed extensive bow before edge gluing, could largely be suppressed while bonded together in the form of panels. This was probably due to the alternate layout with respect to the bow direction of the individual boards within the panels (see figure 6) as well as the applied pressure from the vertical pneumatic clamps during gluing (figure 8). However, the stresses locked inside the kiln-dried panels were released upon the subsequent sawing into single boards, which hence went back to their initial bowed shape again. It therefore seems that end-products that use the full panels, such as CLT, may be a better choice than cutting the edge-glued panels apart into boards again.

### 4.4.4 Cup

**Table 8:** ANOVA table showing the significance of pith presence, green edge gluing, material age and finger jointing for the development of cup

| Effect | SS | Degr. of Freedom | MS | F | p |
|---|---|---|---|---|---|
| Intercept | 285.5393 | 1 | 285.5393 | 627.6779 | 0.000000 |
| Pith | 0.4440 | 1 | 0.4440 | 0.9760 | 0.324228 |
| Edge-glued | 7.4391 | 1 | 7.4391 | 16.3528 | 0.000072 |
| Finger-jointed | 0.0228 | 1 | 0.0228 | 0.0501 | 0.823012 |
| Pith*Edge-glued | 2.0715 | 1 | 2.0715 | 4.5535 | 0.033905 |
| Pith*Finger-jointed | 0.0228 | 1 | 0.0228 | 0.0501 | 0.823012 |
| Edge-glued*Finger-jointed | 0.1327 | 1 | 0.1327 | 0.2917 | 0.589676 |
| Pith*Edge-glued*Finger-jointed | 0.7736 | 1 | 0.7736 | 1.7005 | 0.193516 |
| Error | 105.0851 | 231 | 0.4549 | | |

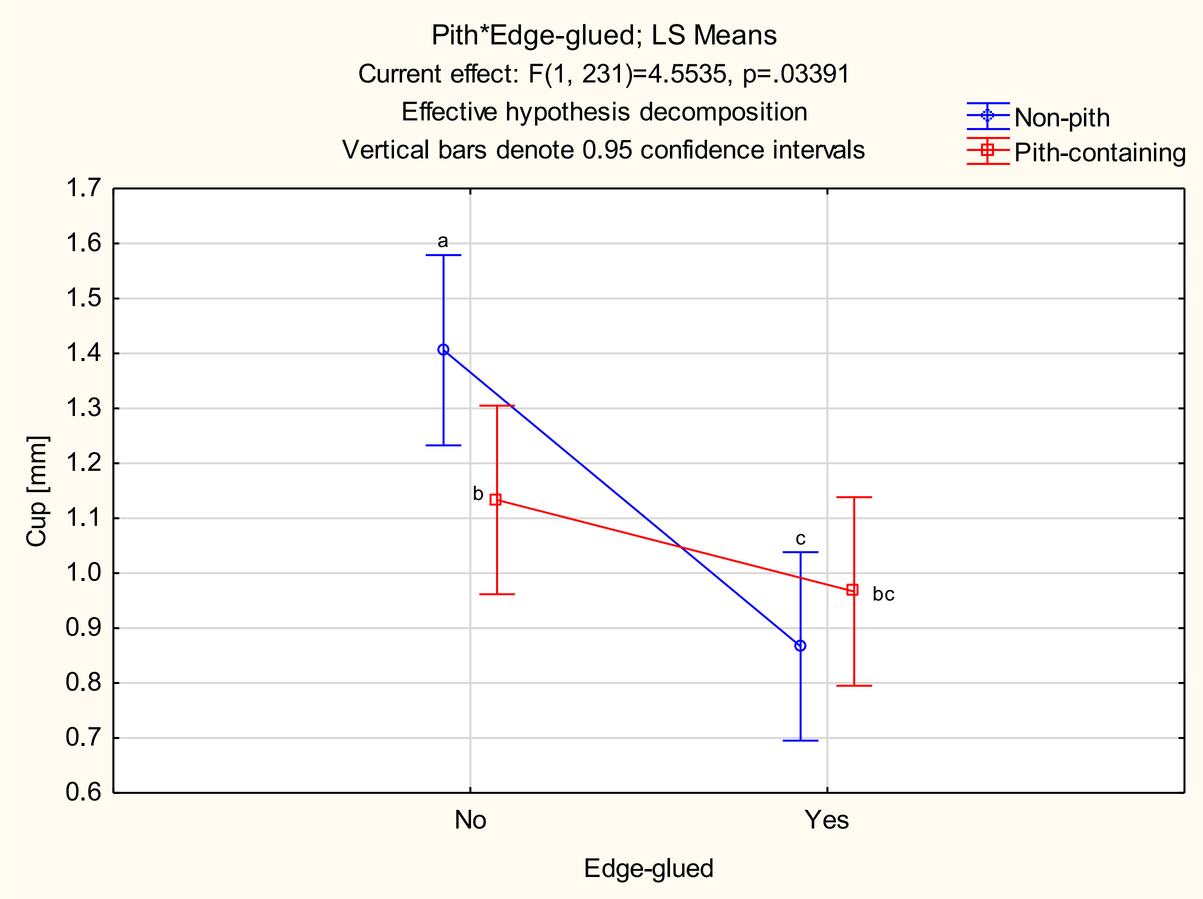


*Figure 17: Significant two-way interaction between the presence of pith and edge gluing of the green boards for the development of cup.*

The two-way interaction between the presence of pith and edge gluing of the green boards in regard to cup development had a p-value of 0.034 and thus was statistically significant at a 5% significance level.

Figure 17 shows that the edge-bonding of green boards in general had a positive effect on the reduction of cup. This trend was however significantly more pronounced for boards with a greater distance from the pith (P0) than compared to pith-containing boards (P1).

The decrease in cup for green edge-glued material (EG1) was probably owed to the alternate arrangement of the single boards with respect to bow. Since both bow and cup are related to the growth ring orientation, cup was also in alternate directions for neighbouring boards (see figure 6). Since cup is the result of unequal shrinkage (see figure 3) and most of the shrinkage happens during the kiln drying stage, the preceding edge-bonding of the boards was likely to have contributed to reduce their deformation.

When the lumber was kiln-dried without prior to edge-bonding (EG0), boards with a greater distance from the pith (P0) developed slightly more cup than pith-containing boards (P1). This can be explained by the anisotropic shrinkage of wood, which is more pronounced in the tangential than in the radial direction (Time 1998). Whereas flat-sawn boards, which contain a centred pith, tend to shrink more equally around it, unilateral warp (in the form of cup) is caused by the unequal shrinkage of boards taken from an area more far from the pith (P0) (see figure 3).

### 4.4.5 Twist

**Table 9:** ANOVA table showing the significance of pith presence, green edge gluing, material age and finger jointing for the development of twist

| Effect | SS | Degr. of Freedom | MS | F | p |
|---|---|---|---|---|---|
| Intercept | 1420.789 | 1 | 1420.789 | 909.7218 | 0.000000 |
| Pith | 13.479 | 1 | 13.479 | 8.6308 | 0.003640 |
| Edge-glued | 2.848 | 1 | 2.848 | 1.8235 | 0.178220 |
| Finger-jointed | 4.910 | 1 | 4.910 | 3.1435 | 0.077547 |
| Pith*Edge-glued | 6.638 | 1 | 6.638 | 4.2503 | 0.040362 |
| Pith*Finger-jointed | 0.745 | 1 | 0.745 | 0.4770 | 0.490482 |
| Edge-glued*Finger-jointed | 0.984 | 1 | 0.984 | 0.6300 | 0.428169 |
| Pith*Edge-glued*Finger-jointed | 4.684 | 1 | 4.684 | 2.9990 | 0.084650 |
| Error | 360.772 | 231 | 1.562 | | |

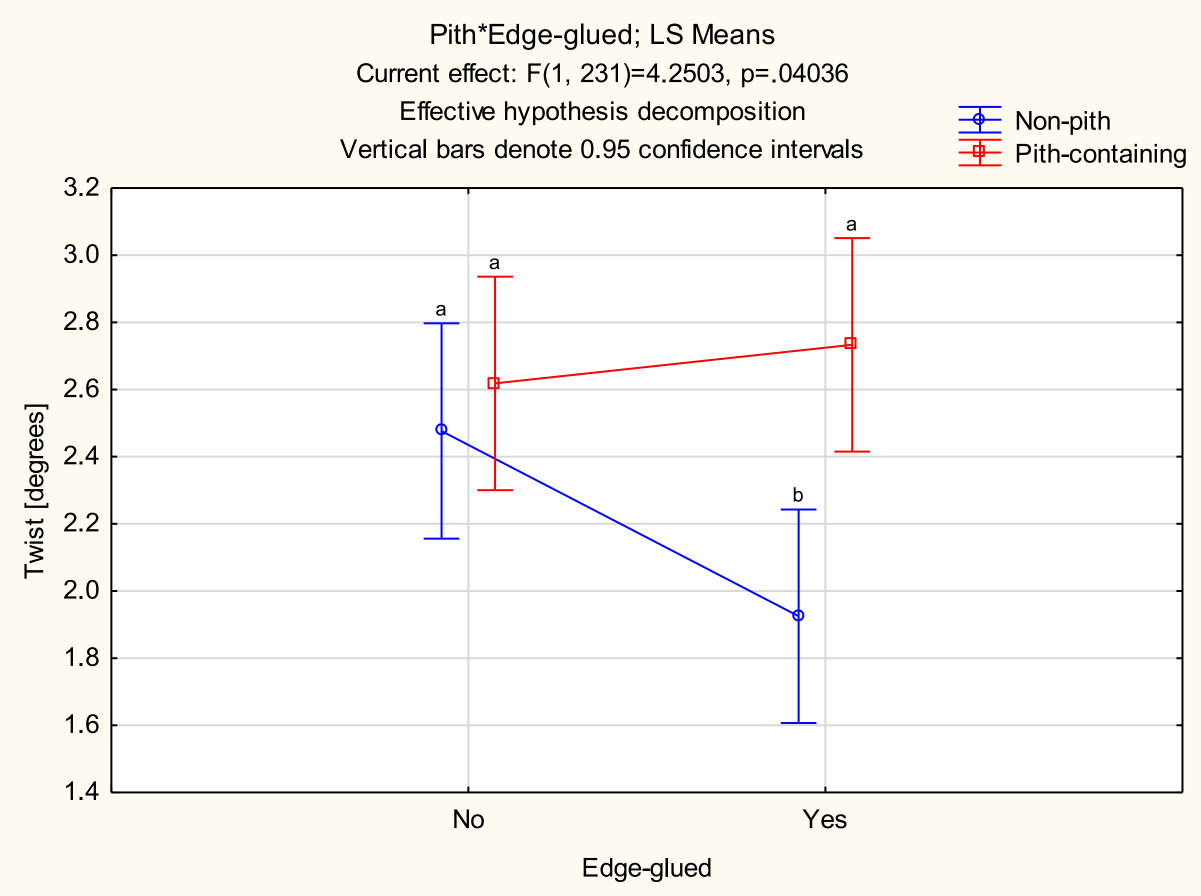


*Figure 18: Significant two-way interaction between the presence of pith and edge gluing of the green boards for the development of twist.*

The two-way interaction between the presence of pith and green edge gluing was found to be statistically significant at a significance level of 5% regarding the development of twist, showing a p-value of 0.04.

It can be observed in figure 18 that edge gluing reduced the amount of twist for non-pith boards (P0), whereas it had no significant effect on the twist development of pith-containing boards (P1). According to Säll (2002), twist development in sawn timber boards is owed to spiral grain, which has its origin in the growth of a tree when the direction of the fibres deviate from the stem axis. However, spiral grain alone has only little effect on wet material as deformation is created by drying the boards below FSP, due to unequal shrinkage between the radial and the tangential direction of the wood. Since during this period of drying the boards of the edge-glued group (EG1) were restricted to warp, this can explain the reduction of twist for the non-pith material (P0), which remained in a more straight shape after sawing the edge-glued panels into single boards.

No specific explanation why twist did not decrease for edge-glued pith-containing boards (P1_EG1) could be found by the author. However, although the slope of grain of the boards was not measured within the scope of this study, spiral grain theoretically occurs in a different form for pith-containing boards (P1) (opposite direction on the two wide faces) than for boards with greater distance from the pith (P0) (same direction on both wide faces). Furthermore, it is well known that various properties of the pith-surrounding juvenile wood differ significantly from the properties of mature wood (Walker et al. 1993), which might be linked to the different behaviour of the two groups (P0 and P1).

According to Crafford (2013), twist was a critical defect in young *Eucalyptus grandis* boards, causing the failure to comply with the SANS 1707-1 (2010) requirements for sawn eucalyptus structural timber. Since the results showed that the edge gluing before kiln drying could at least partially contribute to the reduction of twist development, it should be considered a possible measure to inhibit this defect. This might be particularly true for the full edge-glued panels, as no twist was visually observed before they were sawn apart into single boards.

### 4.4.6 Stress-relief grooves

T-tests on groove-cut (FJ0_P1_EG1_G) vs. non-groove-cut boards (FJ0_P1_EG1) were carried out in order to assess the significance of stress-relief grooves on every investigated defect (check, split, bow, cup and twist).

**Table 10:** T-test table showing the significance of stress-relief grooves in regard to the development of check, split, bow, cup and twist

| Variable | Mean N | Mean Y | t-value | df | p |
|---|---|---|---|---|---|
| Check | 58.03333 | 44.50000 | 1.011326 | 58 | 0.316061 |
| Split | 4.73333 | 4.76667 | -0.013341 | 58 | 0.989402 |
| Bow | 3.60000 | 3.60000 | 0.000000 | 58 | 1.000000 |
| Cup | 1.00000 | 1.13793 | -0.825805 | 57 | 0.412358 |
| Twist | 2.86086 | 2.29539 | 1.689690 | 58 | 0.096456 |

It turned out that the presence of groove-cuts in FJ0_P1_EG boards did not have a significant influence on the development of check, split, bow, cup or twist at a 5% significance level. It must therefore be assumed that stress-relief grooves were not able to contribute to the reduction of the above mentioned defects. Together with the severe deformation and degradation of the visual properties and assumingly also strength properties of the lumber (see figure 10), stress-relief grooves would probably not be appropriate for the investigated structural lumber product.

## 5. Conclusions and recommendations

The grading of the lumber, which was conducted according to the SANS 1707-1 (2010), showed that the edge gluing of green *Eucalyptus grandis* boards before kiln drying could not contribute to reduce the total number of board rejections due to the investigated defects, namely check, split, bow, cup and twist. For both, the edge-glued (EG1) and the non-laminated control boards (EG0), an increased amount of the 20 to 25 year old material (FJ0) could comply with the requirements for sawn eucalyptus timber (SANS 1707-1 2010) as compared to the six to eight year old, finger-jointed material (FJ1). Overall, the older, non-pith boards (FJ0_P0) performed best, whereas the younger, non-pith material (FJ1_P0) showed the highest number of board rejections.

Check turned out to be the most critical defect, with about 10% of all tested boards exceeding the maximum permissible dimensions, followed by split (4%), twist (3%) and cup (<1%) and no rejections for bow. However, about 60% of the final check length of the boards was already created before kiln drying and thus could not be influenced by the edge gluing of the green lumber.

According to the factorial ANOVA results, the edge gluing of green *Eucalyptus grandis* lumber was not able to contribute to the reduction of check, split and bow development in the wood during kiln drying. In terms of bow, the lengthwise curvature of the boards was largely suppressed while the boards were edge-bonded together in the form of panels. This was owed to the alternate layout of the boards within the panels with respect to bow direction. However, upon sawing the panels apart into single boards, they went back into a bowed shape.

Cup was significantly decreased by the edge gluing of the green boards before kiln drying. This was likely due to the alternate order of the boards with respect to growth ring orientation within the panels. Twist could be reduced only for non-pith material (P0), but is believed to remain mostly inhibited also for pith boards (P1) alike while edge-bonded together in the form of a panel.

It also turned out that the presence of stress-relief grooves in 20 to 25 year old, pith-containing boards did not have a significant influence on the development of any of the investigated defects. Although the boards containing groove-cuts (FJ0_P1_EG1_G) had a lower rejection rate according to the SANS 1707-1 (2010) compared to their non-grooved equivalent group (FJ0_P1_EG1), a few boards showed significant damage and deformation and thus could no longer be considered for structural purposes due to visual as well as possible strength-related deficiencies.

Overall, cup and twist were the only two defects that were significantly reduced in individual boards by edge bonding them together before kiln drying. If sawn lumber is the intended end-product, it is doubtful that the slight reduction in these two properties will justify the green edge gluing process.

There are, however, other advantages such as the possibility of producing larger dimension lumber from of lower grade material, such as small logs and small pieces of lumber, which might still make this green edge bonding process attractive to lumber producers. A more interesting option might be the production of panel-type products, such as CLT, from these green edge-glued panels. In the case of CLT, the full panels will be used in the production process with the further advantage to position check containing and thus visually unappealing material in the centre layers, whereas higher grade material can be positioned on the visible outside of the product.

It is therefore recommended that further research is conducted on edge-glued *Eucalyptus grandis* panels as an alternative product to structural lumber boards. This is because only little or virtually no warp could be observed in the produced panels before they were cut apart into individual boards. Thus, testing regarding strength and stiffness properties of edge-glued panels needs to be carried out, as well as an assessment of the bonding quality and the recovery rate of panel products for different dimensions. Furthermore, the feasibility of the production of CLT on the basis of edge-glued

*Eucalyptus grandis* panels should be investigated. This would require additional research on the face-gluing of *Eucalyptus grandis* boards, including the assessment of the long-term bonding quality by means of delamination tests as well as strength and stiffness testing of the CLT product for different dimensions.

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# Chapter 4.
# Summary of research results

- In the shear tests, all examined 1C PUR bonds of green edge-glued *Eucalyptus grandis* wood with varying parameters for wood density, moisture content, adhesive spread rate and pressure clearly exceeded the minimum requirements for CLT products according to the EN 16351 (2015) document.

- Generally better shear strength results were achieved for samples with increased MC at about 60% compared to specimens with a MC around FSP.

- If a MC of clearly above FSP was present, an increased adhesive spread rate together with a high pressure would result in strong bondlines. The best results in the shear tests were obtained for these parameters in combination with higher density samples.

- For wood around FSP the lower spread rate recommended for dry-wood bonding showed more stable shear test results.

- The WFP of the green edge-glued *Eucalyptus grandis* samples increased with increasing shear strength.

- Adhesive penetration into the wood cell structure could only be observed by the way of vessel elements. Enhanced penetration could be linked to improved bonding quality.

- Further research on the bonding quality is recommended for additional adhesive spread rates (e.g. 200 g/m$^2$) and pressure values (e.g. 0.8 MPa). Furthermore, different press times should be investigated, as well as the long-term performance of the 1C PUR adhesive bonds by means of delamination tests.

- Producers of green-glued *Eucalyptus grandis* products are advised to employ an adhesive spread rate as stated in the technical data sheet of the manufacturer for dry-wood applications, as more stable results were obtained compared to an increased spread rate.

- The edge gluing of green *Eucalyptus grandis* lumber before kiln drying could not contribute to reduce the total number of board rejections due to the investigated defects according to the SANS 1707-1 (2010) document.

- More boards from the 20 to 25 year old material could comply with the grading requirements for sawn eucalyptus timber (SANS 1707-1 2010) compared to the six to eight year old, finger-jointed boards.

- Non-pith boards from the older material source showed the lowest rejection rate of all groups in terms of grading results.

- Check was the most critical defect, with about 10% of all tested boards exceeding the maximum permissible check dimensions. Approximately 60% of the average total check length per board was already created before kiln drying.

- Cup and twist were the only defects which were significantly inhibited by the edge gluing of the green material before kiln drying. Twist could only be reduced for the non-pith boards.

- Bow was largely suppressed while the boards were edge-bonded together in the form of panels.

- Stress-relief grooves did not have an influence on the development of the investigated defects but caused significant damage and deformation in some of the boards.

- It is recommended to conduct further research on edge-glued *Eucalyptus grandis* panels as an alternative product to structural lumber boards, since these panels were virtually free of warp and can be further processed to various panel-type products, such as cross-laminated timber (CLT).